AIDS IN PRACTICAL GEOLOGY.

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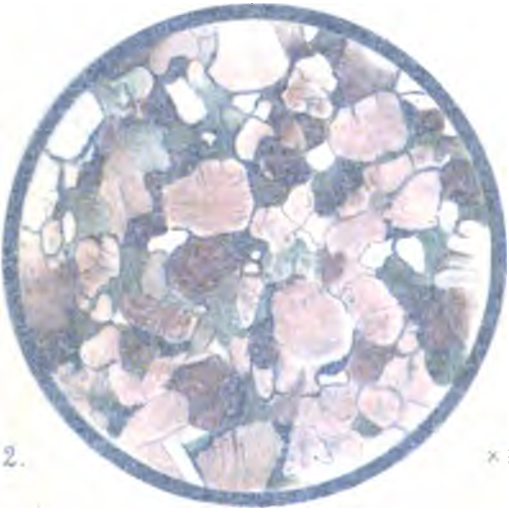

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1. OLIVINE GABBRO, PORTSOY
2. TORRIDON SANDSTONE ULLAPOOL.

AIDS IN PRACTICAL GEOLOGY

BY

GRENVILLE A. J. COLE, M.R.I.A., F.G.S.,

PROFESSOR OF GEOLOGY AND MINERALOGY IN THE ROYAL COLLEGE OF SCIENCE FOR IRELAND, AND DIRECTOR OF THE GEOLOGICAL SURVEY OF IRELAND.

With Numerous Illustrations.

FIFTH EDITION, REVISED.

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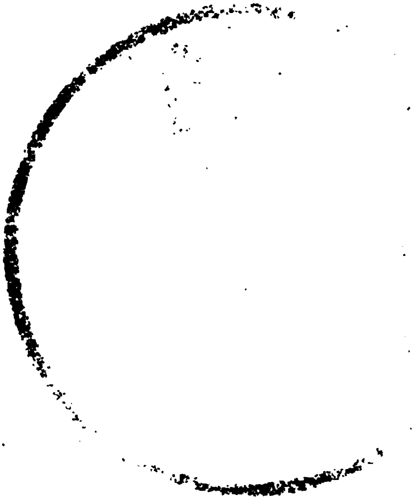

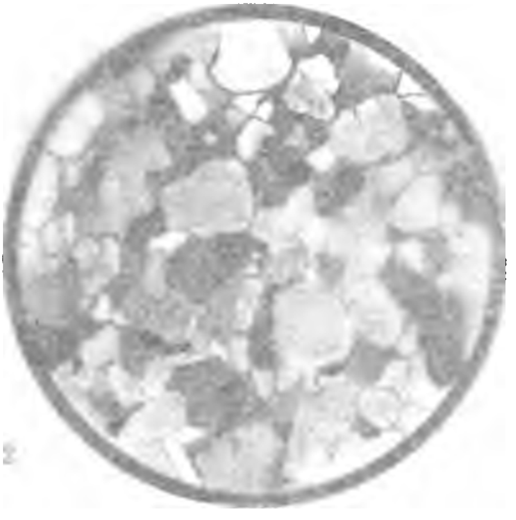

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TO

PROFESSOR J. W. JUDD, C.B., LL.D., F.R.S.,

the Fifth Edition of this Book is inscribed,

IN GRATEFUL RECOLLECTION OF THE AUTHOR'S FIRST LESSONS
IN PRACTICAL GEOLOGY, AND OF THE FRIENDLY HELP
ACCORDED TO HIM THROUGHOUT THIRTY YEARS.

PREFACE TO THE FIFTH EDITION.

While the size of the book has not been increased in this edition, alterations have been made in more than two hundred places, whereby, it is hoped, the fairly wide subject-matter has been brought up to date or more adequately set before the reader. New figures illustrating the microscopic structure of rocks have been introduced, and I have to thank Mr. J. J. Burke of Dublin for skilfully redrawing many of the older illustrations from the specimens originally used. The book has always aimed at aiding those who enquire into the materials and history of the earth's crust, for purposes of research or for any special enterprise. At the same time, the student is not likely to forget that practical geology is fundamentally to be followed in the open country and the open air, and that these "Aids" are intended to help towards the determination of what has been personally gathered from the mountain-side or in the plain. For those who take pleasure in learning from the earth around them, a smaller volume has been written, "Open-Air Studies in Geology," in which special appeal is made to the rock-masses as we meet them in the field. But all the wide developments of geology must rest on patient determinative work; and the invention of a new piece of apparatus for the laboratory, or the correct appreciation of a fossil, may open up the clue to some long-sought secret of the earth.

While certain modern restrictions in nomenclature have been introduced, which undoubtedly tend towards exactitude, the limits of the names of rocks and fossil genera have been kept as wide as possible. It has seemed equally unnecessary to relegate *Terebratula* to an obscure position, because of its imperfect definition a century or more ago, as to set aside

"granite" and "basalt," and a score of familiar petrographic terms. In stratigraphy, I make no excuse for continuing to use De Lapparent's name "Gotlandian" for the beds called "Upper Silurian" by the Geological Survey. The restriction of the name "Silurian" to these strata has raised frequent difficulties, especially in consulting classical maps and memoirs; and, in areas where the Ordovician and Gotlandian beds are not well marked out from one another, there is a great convenience in retaining "Silurian" to cover both the systems. I have again and again found myself thanking Mr. A. Morley Davies in my teaching work for pointing out to me this mode of escape from a very troublesome situation.

The third edition of this book was greatly aided by the advice of Mr. L. Fletcher, F.R.S., as regards the description of the optical properties of minerals. Dr. F. A. Bather helped me at the same time in the choice of genera of fossil crinoids. Most of the kind suggestions made from time to time by Prof. Bonney, F.R.S., Dr. J. J. H. Teall, F.R.S., and Dr. A. H. Foord, are now embodied in this edition.

GRENVILLE A. J. COLE.

DUBLIN, *April, 1906.*

PREFACE TO THE FIRST EDITION.

This little work is intended as a companion to any ordinary text-book of geology; and it is hoped that it may be of special service to those students who have made excursions into the field, and who wish to determine their specimens for themselves. Mr. Joshua Trimmer, in 1841, issued his *Practical Geology and Mineralogy*, with the object of encouraging readers who were beyond the reach of oral instruction. The book necessarily contained some theoretical matter; but at the present day the abundance of excellent text-books has enabled these *Aids in Practical Geology*, while originating in the same idea, to be kept within still stricter limits.

The section on blowpipe-work has been inserted as an aid to travellers; while the description of the hard parts of fossil invertebrates will probably assist those readers who find it impossible to distinguish genera by means of mere names and figures. In arranging the genera thus discussed, those forms have been first dealt with which exhibit most completely the characters of their class or sub-division. Hence highly developed types are often treated of before those which may have preceded them in time, or which may have degenerated from them. By kind permission, I have been able to utilise many of the figures of fossils illustrating Phillips's *Manual of Geology*, and have supplemented these by a few sketches and diagrams explanatory of special features.

A large section of the book has been devoted to rocks and to the ordinary minerals of the earth's crust, since these will

always present themselves to the observer during any expedition or in any country. As for the names used for igneous rocks, I have endeavoured to retain the comprehensive terms of pioneers, such as d'Aubuisson, Brongniart, and Haüy. The more exact determinative knowledge of the present day has introduced us to many new rock-varieties; but these can be distinguished by the addition of a mere mineral prefix.

In 1878 Prof. J. W. Judd, F.R.S., organised the instruction in Practical Geology at the Royal School of Mines in London; and it is difficult to express briefly how much this book owes, in respect of any merit it may possess, to the courses then instituted and continuously developed from year to year. My great indebtedness, also, to Prof. Judd's published papers, and to the works of Brush, Lacroix, Lévy, Rosenbusch, Teall, Zirkel, and Zittel, will again and again be apparent in the text. Numerous friends have, in addition, assisted me from time to time. At the risk of passing over some of the most generous, I must express my sincere thanks to Messrs. J. E. Duerden, L. W. Fulcher, J. W. Gregory, and T. H. Holland. And let me add, with Isaak Walton, that "I have found a high content in the search and conference of what is here offered to the reader's view and censure; I wish him as much in the perusal of it."

GRENVILLE A. J. COLE.

DUBLIN, *December*, 1890.

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AIDS IN PRACTICAL GEOLOGY.

PART I.

THE SAMPLING OF THE EARTH'S CRUST.

"A fossil shell may interest a conchologist, though he be ignorant of the locality from which it came; but it will be of more value when he learns with what other species it was associated, whether they were marine or freshwater, whether the strata containing them were at a certain elevation above the sea, and what relative position they held in regard to other groups of strata."—CHARLES LYELL, *Principles of Geology*, vol. i., 1830.

CHAPTER I.

ON CERTAIN OBSERVATIONS IN THE FIELD.

THE examination of the features presented by the Earth's crust in any locality, with the object of learning something of its past history, must always be one of the most delightful of occupations; and the material advantages arising from a correct determination of minerals and rocks are obvious to every traveller. Such aids in determinative geology as are given in the following pages may be applied in any halting-place, or in cities after the return from an expedition; but in any case observations made on specimens are of slight importance if uncoupled with knowledge of their true position in the field.

The Museum-Curator, for instance, has duties of an invaluable character. He brings together, collates, and arranges the types and varieties described by authors, adding to them by his own special knowledge, and thus forming a series with which any new specimen can be easily and accurately compared. To

him the Earth becomes a great reality, for he surveys it through the extent of his collections and his studies; but the ordinary student, gathering together a few relics from the curiosity-cabinets of relatives and friends, finds that they appeal to him but little; they have no associations, they have long been separated from their kindred, they are "fossil" in the worst of senses. But let him, having a knowledge of first principles and of museum-types, go out to see things for himself. Furnished with the maps and books of experienced workers, let him re-examine the evidence on which they have relied. A week's holiday thus spent amid varied surroundings, as on the Welsh border, or in Antrim, or around Edinburgh or Bristol, will provide material for long and careful study. Once in the field, the complexity of the subject will dawn upon him; but at the same time he becomes assured that, wherever he may wander, he will find congenial work. The first visit to a district commonly raises numberless questions, when the specimens gathered are examined at his leisure; and the suggestions of the laboratory or the microscope must be tested in a second or third excursion by re-examination of the relations of the rock-masses in the field.

In the field itself broad names are assigned to objects, detailed determination being left for comparative and instrumental work; but in these after-hours of study every scene comes back vividly before us, and even the lichens that may yet cling in hollows and betray the collection of an imperfect and weathered specimen, serve their turn with the naturalist and remind him of the wide, open-air, and eminently natural character of his work.

The art of observing in the field, and of balancing the evidence of various exposures, must be to a great extent learnt by oral tradition and personal guidance; and the study of any geological map, with its outliers, its sinuous outcrops, its inliers, its repetitions by faults or foldings, should be carried on, wherever possible, in the actual district that has been mapped. The practical construction of maps, and of sections from them, is discussed in Sir A. Geikie's *Outlines of Field Geology* (Macmillan & Co.), and Penning's *Field Geology* (Baillière, Tindall & Cox).

The examination of a country like Britain, or any part of western Europe, from the point of view of a student anxious to grasp the salient features, the connexion between underground and surface characters, has been immensely facilitated by the modern development of cycling. Traverse after traverse of a country may be made with some handy geological map carried in a capacious tool-bag, together with a hammer, heavy enough

to investigate each wayside exposure. The physical geology, dip-slopes and escarpments, alluvial plains or mountain-gorges, become very real to travellers on the road; and the repetition of the same features in the same order in successive traverses comes upon one with admirable distinctness, and gives a key to the structure of wide areas. When the general grouping of the strata has been grasped, attention can be paid to some limited district. But even here a bicycle or tricycle ready to hand is of considerable value. Though days and weeks may be spent on foot up and down rugged exposures, or across broad cultivated lands set with little quarries, as in the Cotteswolds, every now and then comparison becomes desirable with some distant point, and the road is taken without delay. The intervening country may be reviewed in passing; when local work is completed, a different route can be taken in returning; and thus hints are received and sections examined which otherwise might have entirely escaped.

And this matter applies also to geological observations in districts inviting by their wildness. If the student of the Grampians, the Juras, or the Alps, can find time to approach them mile by mile along the highways, following up the rivers that flow from them, tracing afar off the limits of the lowland, the first curvings of the foot-hills, the change from pasture to moorland, from moor to desolate crag, he gains a most vivid appreciation of his surroundings when he arrives at the locality of his work. And just as the district in which he finally settles acquires dignity from its wide associations, so his very specimens and chips, whenever studied, come to have a truly geological, not merely mineralogical or palæontological significance. Even a microscopic slide, amid such memories, seems to assume its place in nature.

The **instruments** used in the field should be noticed here. First in importance is the hammer, which may vary much in size and weight with the work proposed, and which may easily err in being too heavy, as well as in being too light. Before undertaking any long expedition, the head and shaft should be well tested, and the form of handle that cramps the hand least should be selected. A handle too small in circumference is liable to cause blisters, or at any rate to pain the hand, during long use on refractory materials.

For most kinds of work, a flat end to the head about 1 inch square seems most suitable; the other end should be chisel-shaped, and there are many reasons, easily seen in practice, why the chisel-edge should run horizontally, not vertically, when the

hammer-handle is held upright. A strong side-reason when working in hill-districts is that a secure hold can often be obtained in ascending or crossing steep grass-slopes, by driving the chisel-end at each step into the soil.

A sharp pick-like termination may sometimes be useful, in place of the chisel-edge, for splitting open lumps of soft rock when seeking fossils, or for laying hold of and bringing down materials that are beyond the reach of the arm alone. But for general purposes, trimming of specimens, wedging out blocks, and so forth, the chisel-edge, some 1 inch or so broad, is invaluable.

Where much collecting is to be done, weight becomes an object; and the reduction of specimens to a convenient minimum size in the field is always desirable, since any accidental fracture can be remedied by at once securing another specimen. Hence a light trimming hammer proves a great additional convenience, and the risk to specimens during trimming, particularly when they contain fossils, is thus very much reduced.

Though many geologists prefer to dispense with a chisel, there is no doubt of its convenience where blocks of rock have to be worked out from a cliff-face, or in any place where the hammer fails to get an easy hold. A good "cold chisel," some 4½ to 5 inches in length, is suitable. If it is too short, it may become driven in down joint-cracks before its work is done and before the block is wedged away from the parent-mass.

Elaborate hammer-belts seem quite unnecessary. The specimen-bag is commonly slung by a strap passing over the right shoulder, so that it can be steadied and partly supported by the left hand when it becomes full and heavy. An additional strap for the hammer cumbers the chest, and even in a belt the head has to be prevented from touching and wearing through the clothes. It is simple enough to slip the hammer into the side-bag itself, the handle projecting from the forward end under the flap. The left hand, by resting on the handle, can then easily, during long walking, keep the bag from rubbing unpleasantly on the hip.

The bag itself should be light and strong, with two strongly attached buttons, rather than straps, to close the flaps, so that no time is lost in opening. On moving from each collecting-place it must invariably be closed, as a slight slip or twist when climbing may deprive the observer of valuable spoils. In rounding rocky slopes it is best to keep the bag slung well upon the back; if on the outside, it tends to destroy the balance in the wrong direction; if on the inside, it thrusts the body away from the

rocks, and is also liable to catch during any rapid movement. In jumping, as across little stream-cuts, it will soon be found that the hand should steady it from below.

A receptacle that proves extremely light and satisfactory is the rubber "game-bag," covered with thin cloth, which is procurable at some water-proof dealers.* The price is about 6s., and the supporting rings and straps are generally strong. Though liable in old age to be finally cut through by sharp rocks, the material, even when perforated, does not fray away.

It is scarcely necessary to mention a **walking-stick** as part of the geologist's equipment, for it is indispensable on steep or roughish ground. It should, at anv rate, be never left behind where long slopes and taluses are in question, since its use will make observations possible that might otherwise involve genuine risk. Among rocks it may sometimes be necessary to throw it over in advance; but to descend dry grass-slopes without a stick is undoubtedly time-consuming and vexatious. Mountaineers will forgive our reminding the geological student, who will often find himself in situations all the more pleasant for being unfamiliar, that a steep hill-side should be traversed with the stick in the inside, not in the outside hand.

A **compass** is a necessity for the pedestrian. It may be combined with the **clinometer**, as in the convenient box-instruments often made. Many of these, however, do not allow sufficient length in the edge which is to be held co-incident with the line of dip observed. Any one can construct a clinometer from an ordinary protractor; a swinging index, or even a weighted thread, being hung from the centre of the straight edge so as to reach the graduated arc. Of course the 90° marked on the protractor reads as 0° when a dip is to be taken; thus, if the index points to 84°, the dip is 6°, and so on.

In observing a dip, the plane of the graduated arc of the clinometer must be held parallel to a vertical rock-face on which the beds appear exposed, and the distance between the eye and the rocks should be reasonable, in order that the straight edge may appear coincident with a considerable length of the dipping strata. The instrument is tilted until this edge appears to lie along some well-marked line of stratification; the plummet or index then points to an angle equal to the angle of dip observed. Several observations are desirable as checks to one another; any evidences of lenticular or current-bedding must be noted; and the compass-bearing of the face of rock utilised must also be observed.

* Messrs. Walkley & Co., 5 Strand, London, supply these.

The dip thus found is very probably only an apparent dip, and is less than the true dip, which runs in some other direction. Two or more observations taken near to one another will settle this point. Thus where there are two dips seen on different walls of the same quarry, or in closely adjoining quarries, and where these are evidently not due to mere local slippings or to the very common creep of the higher beds down the slope of a hill-side, then the direction and amount of the true dip can be found by the simple geometrical method of Mr. W. H. Dalton.*

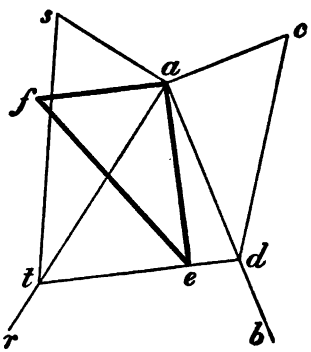

Fig. 1.

The directions of the walls, or rock-faces, on which the dips are seen are determined with the compass, and two lines are drawn to represent them on paper, giving the angle *r a b* (fig. 1). Should one dip in the actual quarry-sections incline towards *a* and the other away from *a*, one of the lines drawn must be produced, so that the dips represented in direction by the lines *a b* and *a r* both either incline towards or away from *a*.

Draw *a c* perpendicular to *a b*, and of any convenient length, say, for greater accuracy, about 3 inches; and draw *a s* perpendicular to *a r* and equal to *a c*. From *c* and *s* draw lines making with *a c* and *a s* respectively angles equal to the complements of the observed angles of dip, and cutting *a b* and *a r* in *d* and *t*. Then the angles *a d c* and *a t s* represent the angles of observed dip along the directions *a b* and *a r* respectively.

Join *d t*; this line represents the strike of the beds. *a e*, drawn from *a* perpendicularly to it, gives us the direction of true dip. Draw *a f* perpendicular to *a e* and equal to *a c* or *a s*; join *f e*. The angle *a e f*, when measured with a protractor, gives the amount of the true dip.

The matter is clear if the three triangles *a s t*, *a c d*, and *a f e* are imagined as bent up so as to stand perpendicularly to the plane *a t d*, which remains horizontal. The points *s*, *c*, and *f* coincide, and a plane laid upon the dipping lines *s t*, *f e*, and *c d* will represent truly a surface of one of the strata observed in the field, when both the apparent dips were inclined away from *a*.

* *Geol. Mag.*, 1873, p. 333.

d t is a horizontal line in this surface, and is therefore the strike; the line *f e*, now perpendicular to it, and also in the same surface, represents the true dip both in compass-bearing and in inclination to the horizontal.*

If both the observed dips are inclined towards the point *a*, it is clear that the same construction suffices, only the arrow set down upon the map to indicate direction must point along *a e* towards *a* and not away from it.

Graphic methods like the foregoing serve the geologist far better than any system of elaborate tables. Provided the scale of the drawing is sufficiently large, the errors of observation in the field, owing to the small exposures studied, will be greater than any that can be introduced afterwards by measurement from a carefully constructed drawing.

To find the relation of the point where observations are being made to features marked upon the map, and thus in one's notes to localise the observation, is often difficult in a wide and open country. Even the map on the scale of 6 inches to a mile cannot represent every rock and projecting boss, and measurements must be made extending from some recognisable point to

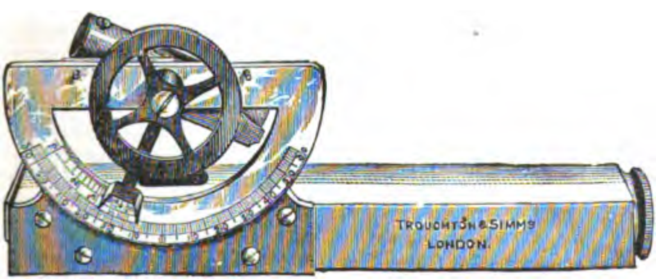

Fig. 2.

the place of observation. The **tape-measure**, so important in determining the thicknesses of beds on faces of a quarry, is often of use in direct measurement on the surface of the ground, for which purpose it should be at least 40 feet in length. Mere pacing over the interval is sufficiently accurate in many cases; but where the position in azimuth can be found, and it is a

* Though dip and strike are commonly considered together, the *Dip* may be defined independently as the line of greatest inclination to the horizon, and the *Strike* as the direction of a horizontal line, in the plane surface of any bed.

question of how high above or how far below some known point we are standing, the little instrument known as Abney's level (fig. 2) is of constant service. This level * is a combination of a contouring-glass with a graduated arc and rotating spirit-level, so that fairly accurate altitude-readings can be taken. Within a horizontal tube, square in cross-section, is an inclined metallic mirror, which extends half-way across the tube, its lower edge being straight and horizontal. Through an aperture in the upper side of the tube this mirror reflects the bubble of a little spirit-level, which is attached to an index-arm and can be rotated by the finger in a vertical plane. The index-arm, bearing a vernier reading to 10 seconds of arc, moves over a semi-circle graduated in degrees.

When the index is at zero, the spirit level is accurately parallel to the eye-tube. On looking through the latter, and shifting it in altitude till the image of the bubble is exactly bisected by the horizontal edge of the mirror, any object seen through the tube to coincide with that edge is on the same horizon or contour as the eye of the observer. By proceeding nearer to that point and levelling on from it to one more distant, a horizontal chain of points may be established.

By this means, even when only scattered heights and not contour lines are set down upon the map, the height above sea-level of some point near the place of observation can finally be determined. Such a point being known, the use of the level will determine the height of any other, provided it is reasonably accessible. Keeping the index still at zero, the observer, if the point to be determined is above that already ascertained, stands upright at the known point and levels through the tube at the slope above him. Selecting some prominent stone or grass-tuft that appears on the edge of the mirror when the bubble is bisected, he walks to this point and repeats the observation. By a succession of such observations, which may be made along the direct line between him and his goal, or along as zigzag a course as the nature of the ground may dictate, he finally arrives at the point the height of which is to be found. The number of times the observation has been repeated, multiplied by the height of his eye above the ground, as measured with a tape when standing upright, gives the total height that must be added to that originally ascertained.

* Made by Messrs. Troughton & Simms and other opticians; price about 40s. Messrs. Elliott Brothers, London, make a highly useful form, price 80s., in which a small prismatic compass, for horizontal surveying, is attached to the tube.

Similarly, if the unknown point is below the known one, the levelling starts from the former and rises to the latter.

So far, a simple level, about 1 foot long, with sights at each end and a little folding mirror just above it to show the bubble when it is being held level in the hand, will serve for these and similar contouring observations. But the convenience of Abney's level is that it can be also used for reasonably accurate determinations of the heights of cliffs, and the thicknesses of great divisions of strata displayed on them. Thus, if a level shore can be obtained, two observations of altitude taken at a measured distance from one another will determine the height of any part of a rock-face. The tube of the instrument is directed towards the point in question, and the spirit-level is rotated until the bubble appears bisected. Removing the instrument from the eye, the index will indicate the angle which the eye-tube made with the horizontal during the observation. In drawing out the results graphically, the height of the eye from the ground will again have to be taken into account.

Moreover, this level works excellently as a clinometer, and thus enables one to dispense in practice with any other instrument for measuring angles. Since, in the forms made, the bubble is not always visible when the graduated arc faces the observer, the instrument should be turned round so that the spirit-level is nearest to the eye. The edge of the eye-tube, which for this purpose might easily be made a little longer, serves as the straight edge of the clinometer. When it is adjusted so as to appear coincident with the line of dip, rotate the spirit-level until the bubble is seen to lie centrally in its tube. The angle at which the main tube has been inclined to the horizontal will be accurately shown by the position at which the index now stands. After the spirit-level has been rotated so as to become horizontal, the coincidence of the straight edge and the dip must be carefully checked, lest the hand supporting the instrument should have shifted its position.

A common triplet pocket-lens, or any useful form that will bear rough usage, must always be carried in the field, as indeed it should be carried by the geological observer every day of his life, whether in town or country. A note-book without ruled pages, so that outline-sketches may be added to the ordinary notes, can be kept ready in the side-pocket.

Seeing that the page of a field note-book is necessarily small, it is a good plan to carry sheets of the size of writing-paper in one's pocket-book, folded in quarters. Such paper can be unfolded to suit the nature of the sketch.

Facility in drawing the outlines of scenery comes with practice, and a sketch or photograph should be made of every critical area or section. The points on a sketch may be lettered to facilitate reference in the notes or on the labels of specimens.

Lastly, the geologist who knows how to treat and use a fountain-pen will never be without it in the field. For precision of line in sketching, for writing on loose pieces of wrapping-paper, which may be waving in the wind, or on smooth surfaces of the specimens themselves, there is no comparison between the utility of an ink-pen and a pencil. Specimens may undergo various hardships during travel, and may remain packed up for months; but their labels, if written in ink, will be always black and legible.

CHAPTER II.

ON THE COLLECTION AND PACKING OF SPECIMENS.

EXCEPT in the case of brilliant examples of minerals, or of fossils exhibiting characters in an unusually fine state of preservation, specimens are of little utility or interest to the geologist unless gathered actually *in situ*. A talus-heap, still worse a road-heap, the materials of which may have come from anywhere, affords very tempting but very misleading material. Some "specimens" seen in their true position are, however, far too large to be carried away. In such cases a sketch giving dimensions, or a photograph, must suffice, and chips from various parts may serve subsequently as illustrations of the whole.

Hints are scattered through the following pages as to the points to be regarded in selecting specimens of various kinds. We need only note here that subsoils may be collected in artificial cuts or on the banks of streams, some 2 feet or so below the ordinary cultivated and altered surface.* Where the physical characters of a loose material, such as a soil, are to be investigated, the following method has been found satisfactory. A box of thin iron is made, like a biscuit-box, 20 cm. long, 10 cm. deep, and 10 cm. wide, with two lids in place of a fixed bottom and a lid. An excavation to the required depth is made with a spade, and a good block of the soil is lifted out, without

* Von Richthofen, *Führer für Forschungsreisende* (1886), p. 28.

disturbance, on the spade, which is now laid on its back on the ground. Place the frame of the box on the block of soil, so that its length lies perpendicularly to the original surface, and press it carefully down, whereby it cuts off the extra material round it, and becomes filled with the soil in a natural state. The frame may be driven down by taps with a hammer on its corners. Smooth off the material that is now protruded through the frame above the level of its sides, and put on one lid. Turn the spade and box carefully over, and remove the spade; smooth off this side similarly and affix the second lid. Wipe the outside of the box, label it, and enclose in a bag or large stout envelope. In this way we obtain a soil-sample that we know occupied exactly two litres in its field-condition.

Well-developed crystals of minerals are to be hoped for only in cavities and on the walls of open joints; while rock-specimens should be broken out from larger masses, so as to secure fresh unweathered surfaces. It is often useful, however, to show the amount of resistance of the rock to atmospheric action by collecting the surface-crust also. The difference of colour between such crusts and the interior is often striking, as may be seen in brown clay-blocks with blue cores, or in the blue-grey "felstones" of Wales, which weather to a porcellanous white.

Fossils may often be gathered in a good washed-out condition on the loosely coherent banks immediately below the outcrop of the beds in which they properly occur; but no pains must be spared in collecting from the horizons themselves, although specimens thus obtained may emerge fractured and otherwise obscured. The *assemblage* of forms should be fairly represented in a collection, since it is well known that the mere fact of the occurrence of a particular species does not necessarily mark a zone.

Curious errors of locality often arise, which are due to the indefatigability of man. Thus remarkable rocks are carried for long distances to decorate the window-sills of cottages, and afterwards become cast out upon the hills to puzzle the wandering observer. Similarly the glassy slags of long-forgotten furnaces have again and again been produced as evidence that volcanic rocks occur in such and such an area. As to the shells of recent edible molluscs, especially the oyster, no locality seems too anomalous for their discovery.

The labelling of specimens in the field may be done by attaching numbers to them on strongly gummed labels, and describing them, with corresponding numbers, in the note-book. Each specimen should be wrapped in newspaper to prevent friction with its fellows in the bag. Hence a less cumbrous, though at

the same time less neat method, is to write all the description on some part of the plain white edge of the wrapping-paper; this should be folded in so as to escape tearing, and should be always kept as carefully as the specimen itself. It will form, in fact, when subsequently torn off on unpacking each specimen, the "original label" drawn up on the spot to which all future reference must be made. Experience shows that specimens thus labelled on infolds of their wrappers may be sent thousands of miles by rail or sea without any risk of confusion or loss of the observations recorded. Dr. Blanford advises travellers in tropical countries to poison their labels by washing in a weak solution of corrosive sublimate, to prevent their being destroyed by mites and insects. (See the admirable series of papers entitled *Hints to Travellers*, published by the Royal Geographical Society, 7th ed., p. 382.)

Charles Darwin suggested from his experience that during a voyage the specimens from distinct localities should have their wrapping-papers marked externally with characteristic signs, a practice of great assistance during unpacking.*

The original label, or the note corresponding to it, should be as full as possible, and may even contain cross-references to specimens collected in the same series. If the locality is an unknown one, as in long traverses and in wilder regions, the hour and day of finding should be noted in each case. Even if this goes on from day to day during the passage of an expedition, some idea can be gained respecting the relative positions of the places studied along the route.

The practice of noting the day, month, and even year, on the label of every specimen, is, indeed, of continual use in after reference; and in all careful study of an area the hour of the day is of assistance. These minute facts, like so many others, are not, however, for publication. In research-work the duty of the observer is to separate the important facts from the mass of material that has been gathered on the chance of its proving of importance. On the spot everything must be noted; later studies weed out the fundamental from the trivial. The young writer who refers to his specimens by number, and describes them each in detail, has either lost sight of their field-relations, or is working on "drifted" material in the darkness of cabinets and museums.

The transport of geological specimens to their destination is seldom a matter of difficulty, owing to their non-perishable character. In most places cheap sacks or bags are obtainable,

* *Admiralty Manual of Scientific Enquiry* (1859), p. 272.

and these prevent the specimens from shaking on one another, as they may possibly do in a partially filled box. The bag should be of stout fibre, and should be sewn over with strong string just above the specimens. Several such bags may be sent on beforehand to the area of work, since there is often a difficulty in a small town in procuring a box of sufficient strength and of convenient size.

Fossils travel better in a wooden box, unless each can be enclosed in a small box of its own. Small and delicate specimens may be separated in stout corked glass tubes, wrapped round with paper several times; others may be temporarily glued to the bottom of chip-boxes before packing. Where wool is used, it is important to first wrap the specimen in tissue-paper, since the fibres of the wool, if in direct contact, remain upon the specimen for years.

The development of the parcel post has greatly facilitated the transport of small series of specimens from foreign countries. It should be noted that in Italy a linen cover is required to parcels, paper alone being inadmissible; hence here, and elsewhere as a safeguard, a few calico bags to enclose the series sent form a handy addition to one's equipment.

PART II.

THE EXAMINATION OF MINERALS.

"La Minéralogie, étant une branche de l'histoire naturelle, les mêmes principes qui dirigent les naturalistes en général doivent diriger aussi le minéralogiste. Il cherche a connoître et à apprécier la place que les divers espèces de minéraux tiennent dans cet ensemble d'êtres qu'on nomme la nature, et à s'instruire du rôle qu'ils y jouent."—ALEXANDRE BRONGNIART, *Traité de Minéralogie*, 1807.

CHAPTER III.

ON THE OCCURRENCE AND SOME PHYSICAL CHARACTERS OF MINERALS.

A. Mode of Occurrence.—The relation of the mineral specimen to its surroundings should in all cases be observed prior to its extraction. Its occurrence in veins or diffused through a rock-mass, in concretionary forms or in well-developed crystals, its deposition upon earlier-formed constituents, or its inclusion in other substances that have aggregated round it—these are a few of the many points that may help in its final determination. If it appears to be a product of alteration, search should be made for examples of the mineral or minerals from which it may reasonably have been derived. In the case of a substance of especial interest or of commercial importance, a rough sketch or plan of the spot made in the field will often refresh the memory and assist description when the details come to be worked out later.

B. Extraction.—The modes of extracting particular minerals from the mixed or massive aggregates known as rocks will be more conveniently treated of in connexion with the rocks themselves. The mineral particle, whether crystallised or not, having been isolated from its matrix, some one or all of the following methods of examination may be applied with a view

to its determination. The test of hardness, and some observations on form and cleavage, may often be employed without its removal from its surroundings; similarly, the optical tests described are far more commonly applied to minerals occurring haphazard in rock-sections than to preparations cut in known directions from specially extracted specimens.

C. Colour and Lustre—Transparency or Opacity.—It is unnecessary to remind any worker among minerals of the variation of colour in one and the same species. The ores of the heavy metals are by far the most constant in their colouring; but even here the phosphates, carbonates, &c., may assume very deceptive tints. Similarly, a mineral may at times be transparent, at others apparently opaque. Sometimes, however, as in the blacker varieties of zinc blende, a small chip or two flaked off will reveal the true translucent character of the more typical mineral. The blue and blue-green colours of vivianite will similarly become visible when flakes broken from dark crystals are held up in forceps to the light. Some minerals, on the other hand, such as magnetite, are opaque even in the thinnest fragments; and this property becomes accordingly useful in their identification.

The lustre of the faces of crystals or cleavage-planes is often of service, though these are liable to be dulled by filmy products of alteration. The lustres recognised by experts are given in all works on mineralogy.

D. Streak.—The streak of a mineral, *i.e.*, the colour of its powder, can very often be observed by scraping a rough edge of the specimen with an old but clean knife, and spreading out the little fragments, under pressure of the blade, upon white paper. A refinement is to use a slab of unglazed porcelain or the side of a mortar, across which the specimen is drawn; the coloured lines thus given by different minerals may be produced closely side by side, and comparison becomes very easy. The specimens must be free from surface-films and decomposition-products. While most rock-forming minerals yield white or colourless streaks, the results given by many sulphides and oxides of the heavy metals are eminently useful and characteristic, especially when known specimens are ready at hand for comparison. It is scarcely necessary to mention the red streak of specular iron or hæmatite, the orange-brown of limonite, the grey of galena, the purple-red of pyrargyrite, or the browner red of cuprite, as familiar and practical examples.

E. External Form.—The pocket-lens will aid considerably in examining the crystalline form of minerals that have consolidated

under favourable conditions; but the undue development of certain faces, or the almost complete suppression of others, renders the interpretation of natural forms far more difficult than would appear from the symmetrical drawings and models which are first placed before the elementary student. Not even the measurement of the angles will distinguish between an elongated cube and a prism of the tetragonal system; but, in such a problematic case, some other test is certain to be available which will virtually decide the question of the species to which the mineral belongs. In the preliminary examination with the eye or with the lens, twin-structures may occasionally be detected. Thus the characteristic Carlsbad twinning of orthoclase, whether in granitic or trachytic rocks, is very generally observable upon broken surfaces; the basal cleavage is inclined in reverse directions in the two halves of which the crystal is built up; hence the one half will show, as the specimen is turned about in the hand, a series of brightly reflecting surfaces, while the other remains dull or even earthy-looking. From a similar cause, repeated twinning, as in plagioclase felspars, often reveals itself by the appearance of fine alternating duller and more lustrous bands.

It is often useful, and in some cases is absolutely necessary, to determine the angles made by certain planes of the crystal. Even where works of reference are not to hand, the determinations can be forwarded to a friend more fortunately situated; and the angles thus measured and compared will, from their constancy in the same species, serve to explain faces and forms of the most anomalous development. With sufficient practice upon familiar specimens, the well-known contact goniometer of Carangeot * is capable of giving excellent results. In its simplest and perhaps handiest form it consists of two small flat bars of steel or brass, in each of which a slot is cut extending from near one end to the centre, the other half remaining solid. A little bolt is passed through the slots, and the bars are clamped together by a nut. By releasing the nut and drawing back or thrusting forward either of the bars, their cleanly-cut inner edges may be applied to any two planes of the crystal that are not parallel to one another, the measurement being taken when the edges of the bars are perpendicular to that formed by the intersection of the two planes of the crystal. When exact contact has been made, which may be best secured by holding up the crystal and the instrument, and observing that no light passes between the planes and the edges of the bars, the bars are carefully clamped together

* *Observations sur la Physique, &c.*, tome xxii. (1783), p. 193. Haüy and others have spelt the name "Carangeau" and "Caringeau."

and again applied to the planes in question. If no shifting has taken place during clamping, it only remains to determine the angle between the inner edges of the bars.

This is best done by applying the instrument to a semi-circular or circular protractor, which indeed forms an integral part of the contact goniometer. The point of intersection of two adjacent edges of the bars, or else of their middle lines, is made to coincide with the centre from which the angles have been marked off on the protractor. The angle is read off between the prolongations of the bars and not between the edges that were actually applied to the crystal.

Mr. Penfield has recently devised two types of cheap and simple contact goniometers, in which the materials are card and vulcanite. These are sold by Ward, 76 College Avenue, Rochester, New York, at about 2s. each, and are highly serviceable.

In the case of small crystals, and where greater exactitude is required, the **reflective goniometer** must be employed, but is, of course, available only where the faces are reasonably bright. Dull planes of crystals may sometimes, however, be rendered artificially lustrous by cementing to each a little flake of microscopic cover-glass, the gum or cement being spread equally over the face. The instrument, as described in every text-book of mineralogy,* necessarily costs several pounds; but for general purposes of identification the ingenious contrivance of Professor W. H. Miller, based upon the same principles, proves very simple and efficient. A stout brass wire, bent at right angles at the top, is fixed upright near one end of a thick piece of board, which should be about a foot long, with neatly planed edges. A cork is fitted on the bent arm of the wire, as shown at *c* in fig. 3, and through it a shorter wire is thrust, also bent at right angles, and bearing a little plate, *a*, of cork or wood on one end. The crystal to be examined is attached to this plate by wax,† and the wires

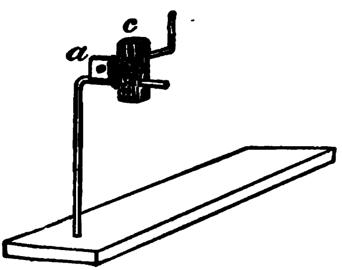

Fig. 3.

* Wollaston's original paper is in the *Phil. Trans. Roy. Soc.*, vol. xcix. (1809), p. 253.

† Mr. Gurney, in his *Crystallography*, recommends bees'-wax and olive oil melted together and stirred until suitable consistency is attained. Only a small admixture of oil is required.

2

must be of such a length that, by the various adjustments of which this simple instrument is capable, the crystal-edge concerned can be brought into an accurately vertical position and immediately over one of the nearer angles of the board.

The instrument is placed on a sheet of paper fastened by drawing-pins to a table at some eight or ten feet distance from a window or similar opening. If the window has a vertical bar, this may be utilised as a signal during measurement; if not, some rod or band can easily be hung across it. A second vertical signal must be set up at the same distance from the instrument, and may conveniently be placed on the same wall.

The eye is brought close against the crystal, and the goniometer is moved about on the sheet of paper until the reflection of the window-bar seen in one of the bright faces concerned appears to coincide with the *second* signal seen beyond it. Now rule a line on the paper along one of the longer edges of the board.

Bring the eye again into the same position as before, and rotate the board horizontally about the point over which the crystal edge has been adjusted. This rotation may be assisted by having a large drawing-pin fixed to the wood, its point projecting downwards exactly below the corner of the board. When, by rotation, the reflection of the window-bar is seen in the second face of the crystal and is made to coincide with the other signal as before, another line is ruled from the same edge of the board upon the paper. Measure the angle between these two lines with a protractor; it is obvious that, no disturbance of the first adjustments having occurred, it will be the supplement of the angle between the two faces. One of the lines may be produced beyond the point of intersection, and the actual angle may thus be measured off at once.

Care must be taken in selecting faces to be measured by any method involving reflection, and at first a little difficulty will be experienced in seeing the image of a signal on so small a surface, however bright. Beginners are apt to hold the eye at far too great a distance, and thus run the risk of confusing the reflections from two adjoining faces. Leaving the discussion of telescopic and other refinements to advanced treatises on mineralogy, an easily constructed form of the ordinary Wollaston goniometer may be described in concluding these remarks. In fig. 4, *a* is a strong wooden upright fixed to a board as a base, and serving as a support to the circular protractor, *b*. A T-piece, *t*, conveniently made of brass tube, runs horizontally through the support, its axis traversing the central point of the protractor,

the bar of which has been partly cut away. The bearings of *t* may consist of bored corks thrust firmly into a larger hole in *a*, and its cross-piece forms a handle by which to turn it during an observation. Two corks, *c* and *d*, work on the prolongation of *t*; *c* carries a pointer, which can be adjusted to some convenient degree on the graduated arc, a semi-circular protractor being thus all that is actually necessary; while *d*, which can itself carry other cork and wire refinements, serves to support the crystal on

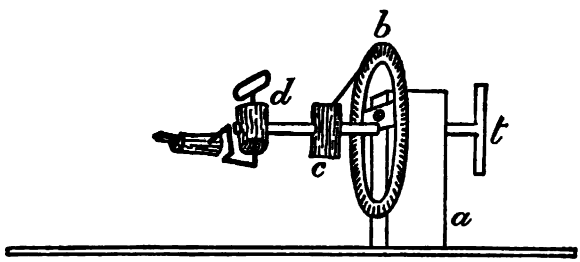

Fig. 4.

its bed of wax. The refinements hinted at may facilitate the adjustment of the important edge so as to coincide with the axis of *t*, and a small cork sliding stiffly on a wire, as indicated in the sketch, will allow of the use of specimens differing largely in size.* The signals used are, of course, horizontal, and the reflection of the first one in a piece of glass backed by dull black paper and placed under *d*, as in the excellent student's instrument devised by Mr. Miers,† will enable the worker to dispense with a second and independent signal.

Any one familiar with tools and with a lathe can easily improve and elaborate such an instrument; but the simple form here mentioned serves well for determinative purposes. Moreover, if the protractor is fixed by two small screws with flattened or ring-shaped heads, such as are commonly used for picture-rings, it is clear that the whole arrangement can be taken down without the aid of tools, and, with a little care in adjustment, set up again ready for use. It is well before using it to test its behaviour upon some known and satisfactory object.

As examples, a few crystal-angles are subjoined, some of the

* A piece of cork may also be thrust into the end of *t*, and from it a fine needle may project, coinciding with the axis of rotation. Against this needle the edge in question may be adjusted.

† Made by Messrs. Troughton & Simms, London. See *Min. Mag.*, vol. ix., p. 214, pls. iii.-v.

figures being sufficiently obvious, but given here as useful tests for practice :—

Quartz; adjacent faces of positive and negative rhombohedron; 133° 44′.
Calcite; cleavage-rhombohedron, measured over a polar edge; 105° 5′.
Fluor-spar; cube face and octahedral cleavage; 125° 16′.
Augite; prism faces; 87° 5′ and 92° 55′.
Hornblende; prism faces; 55° 30′ and 124° 30′.
Orthoclase; principal cleavages; 90°.
Labradorite; principal cleavages; 93° 20′ and 86° 40′.
Garnet; any two adjacent planes of rhombic dodecahedron; 120°.
Spinel; octahedron faces; 109° 28′.
Topaz; typical prism faces; 124° 17′ and 55° 43′.
Zircon; prism and pyramid face; 132° 10′.

F. Cleavage.—The presence or absence of cleavage should be carefully looked for, and the examination of broken fragments of a mineral with the pocket-lens or the microscope will often afford valuable evidence. The planes of cleavage are often marked out on the exposed surface of a crystal, as in hornblende, by traces of incipient decomposition. The use of the basal cleavage in observing the twin-structure of orthoclase has been already referred to. The phenomena described by Professor Judd as "Schillerisation" * give rise to planes of separation, commonly regarded as cleavage-planes, these secondary surfaces of weakness being marked by a pearly or sub-metallic lustre. The shimmering surfaces of broken diallage, ordinary bronzite, murchisonite, &c., are due to this type of separation-plane, and the minute plates that cover them may be well seen in sections under the microscope.

As examples of the utility of the observation of cleavage, we may refer to the following minerals :—

1. Colourless and transparent minerals :—

Quartz.—No cleavage; fracture conchoidal.

Topaz.—Cleavage basal, perfect.

Adularia, Sanidine, and other clear felspars.—Basal and clino- or brachy-pinacoidal cleavages, perfect.

Calcite.—Rhombohedral cleavage, perfect.

Aragonite.—Does not yield the perfect rhombohedra of calcite; brachy-pinacoidal cleavage alone good, prism and brachydome imperfect.

Fluor-spar (often coloured).—Cleavage octahedral, perfect.

Diamond.—Cleavage octahedral, perfect.

Common *Muscovite* and other pale micas.—Remarkably perfect basal cleavage.

* "Tertiary Peridotites of Scotland;" *Quarterly Journal of Geological Society*, London, vol. xli. (1885), p. 383.

2. Darkly-coloured or opaque black minerals :—

Augite and *Hornblende*.—Cleavages prismatic and good.
Tourmaline (*Schorl*).—Cleavage seldom seen ; fracture fairly conchoidal.
Dark Micas.—Like muscovite.
Wolfram.—Clinopinacoidal cleavage, perfect.
Cassiterite.—Prismatic cleavages, imperfect.
Zinc Blende.—Cleavage parallel to rhombic dodecahedron, perfect.

G. Hardness.—The hardness of minerals, though varying at times in the same crystal according to the plane or direction selected for the test, forms none the less one of the best known and most satisfactory means of discriminating between substances closely similar in appearance. The Scale of Hardness devised by Mohs consists of the following minerals, arranged from the softest to the hardest :—*

1. Talc.
2. Gypsum (Selenite).
3. Calcite.
4. Fluor-spar.
5. Apatite.
6. Orthoclase, fresh and cleavable.
7. Quartz.
8. Topaz.
9. Corundum, cleaved.
10. Diamond

Any one seeking to determine minerals should be thoroughly well acquainted with this scale. The relative resistance of each member to the point of a good pocket-knife should be carefully observed in succession, until No. 7 is reached, which is not scratched by steel. If a specimen of each member is passed lightly over the surface of a file, different amounts of material will be removed from each, and the sound produced, at first slight, will become more grating as the higher members are used. It is yet more convenient to draw one edge of a three-sided file lightly across an edge of the member of the scale, the varying amount of resistance and the difference in the sound being very clearly noticeable.

When the scale itself has been thoroughly mastered, the hardness of a mineral specimen may be determined by it. A sharp point of the mineral is selected and drawn firmly across Nos. 9, 8, 7, &c., until a member is found upon which a scratch can just be made. It is always necessary to pass a brush or the finger across the supposed scratch to remove the powder, which may after all be derived from the mineral examined, and not from the member of the scale. A true scratch will appear as a distinct little groove when examined with the pocket-lens.

When a member is found that can be scratched by the mineral under examination, further test should be made of the effect on that next higher in the scale. The use of the file will also help

* The intervals between the successive members of the scale are now known to be exceedingly unequal. See, for instance, T. A. Jaggar, *Amer. Journ. of Sci.*, Dec., 1897, p. 411.

to ally the mineral with one or other member, or to place it midway between two, when its hardness is known as 3·5, 5·5, &c.

With practice, however, the use of the scale itself becomes necessary only in cases of special interest, and the observer relies largely upon certain simple instruments alone. Thus—

(*a.*) Minerals unscratched by a good knife have a hardness (H) of 6 or upwards;

(*b.*) Minerals scratched with a knife have H = 5·5 or less;

(*c.*) Minerals scratched by a bronze coin have H = 3·0 or less:

(*d.*) Minerals scratched by the thumb-nail have H = 2·5 or less.

Few minerals are harder than 7, and the relative degree of resistance to the knife afforded by the softer substances will commonly assign them their places, even when an actual Scale of Hardness is not to hand. Few persons will find serious difficulty in thus distinguishing between degrees 3, 4, 5, and 6, while the thumb-nail decides the lowest degrees of all in an equally efficient manner. A thin soft mineral, such as talc or mica, wrapped about a harder core, as may occur in schists, presents occasionally a difficulty; and it must be remembered that decomposition renders many substances softer than the values given in text-books, which are those of typical specimens.

The hardness of small fragments of minerals can be best ascertained by drawing them across a substance already determined. A thin layer of "electric cement" * or similar material may be melted on to a small bar of wood, and the grains to be tested may be partly embedded in this, and will become firmly set when all is cool. The cement must not be so thick as to allow a grain to become enveloped when pressed down into it. Using the wood as a handle, draw the mineral grain or grains over glass, bronze coins, members of the scale of hardness, &c., and observe the results. Where several grains of different hard minerals have been embedded for comparison, a good deal may be done by drawing a glass slip, such as is used for microscopic mounting, across each grain in succession, and noting the varying depth and character of the scratches thus produced.

H. Magnetic Characters.—The minerals that are attracted by an ordinary magnet in their natural condition are very few, the most familiar being magnetite and pyrrhotine. The former attracts its own powder very freely, affects the magnetic needle of a pocket-compass in a more or less marked manner, and not

* 5 parts resin, 1 part bees'-wax, and 1 part red ochre.

unfrequently exhibits strong polarity. Fragments of pyrrhotine also attract their own powder, are easily lifted by the magnet, and are recognised by their bronze-yellow colour. In the case of feebly magnetic substances, their powder should be spread out on a smooth sheet of paper and the magnet moved about just above the little particles in a somewhat brisk manner. Even if the particles decline to quit the paper for the magnet, movement can be easily seen among them, and they will rise and stand on end as the magnet nears them, falling again after it has passed.

Compounds of iron, nickel, and cobalt, not previously magnetic, become so after reduction on charcoal before the blowpipe. The mass must be cut out, crushed, and then treated as above. The particles extracted from the residue by the magnet can be further tested in borax or microcosmic salt. (See Chapter V.)

If the magnetic properties are so weak that the particles have to be touched with the magnet before they are influenced by it, care must be taken that the magnet is perfectly clean. Examination with the lens will show whether any adherent particles are held by virtue of their magnetism or by mere clinging to a moist or sticky surface. In the former case they will be seen standing up in unusual positions upon the steel.

The place of a bar-magnet can always be taken by a magnetised blade of a pocket-knife. With a knife that has been so treated useful field-observations may be made. Thus the remarkable prevalence of pyrrhotine may be shown in some rock-masses, in place of the more familiar iron-pyrites; and such occurrences may easily be overlooked unless detected on the spot itself.

I. Specific Gravity.—The most familiar method of determining the specific gravity of a body is that involving the use of an accurate balance and a set of chemical weights. The specimen is suspended by a light silk thread from the hook on the underside of a small pan, which replaces the ordinary pan of the balance. It is weighed in air (w) and then immersed in a glass of distilled water; all bubbles are carefully removed,* the water being boiled if necessary, or the vessel being placed for some time under an air-pump; the weight of the specimen when suspended in water is then determined (w'), and the specific gravity $(G) = \frac{w}{w - w'}$. In accurate determinations the water used should

* To remove bubbles with a brush, withdraw the specimen and paint it over, as it were, with water, which should be worked well into the hollows. On again immersing, the bubbles will have broken and disappeared.

be at a standard temperature—English observers have chosen 60° F.

Some few substances of interest to the geologist may be lighter than water—*i.e.*, they have a density of less than 1. In such cases a sinking-weight may be attached, and allowed for as follows:—Let the weight of the sinker in water be a', and the joint weight in water of the specimen and the sinker be b', w being, as before, the weight of the mineral in air. Then in place of w' we have $b' - a'$, and $G = \frac{w}{w - b' + a'}$.

It is often impossible to suspend small mineral fragments directly from the hook; but they may be weighed in a little pan attached to the light silk thread. Let the weights of this pan in air and water respectively be a and a'; add the mineral particles, and let the weight of these together with the pan be determined both in air and water (b and b'). Then $w = b - a$, and $w' = b' - a'$, whence G can be worked out as before.

Mr. Smeeth* has devised an excellent modification of this method, which avoids all risk of loss by the flotation of small grains during immersion. The pan is partly filled with vaseline, which is melted after the mineral particles, already weighed in air, have been laid upon it. The mineral thus sinks in and is completely covered. The difference of weight in water of the pan and vaseline, and the same with the mineral added, gives the weight in water of the mineral powder used.

In the case of substances soluble in water, alcohol, turpentine, or carbon tetrachloride can be used. The figures are worked out as usual, but the result must be multiplied by the density of the liquid used, which may be determined by comparing the weight of a vessel filled with it—preferably a specific gravity bottle—with that of the same vessel filled, at the same temperature, with distilled water.

The use of the specific gravity bottle involves appliances of some delicacy.† The bottle should be small, to suit the probable amount of material to be used; a 25-gramme flask is large enough. Fill it with distilled water, insert the perforated stopper, and wipe off any water that has flowed over. Place the powdered or fragmentary specimen on the pan of the balance on a scrap of smooth paper, a counterpoise to the paper being laid in the other pan. Weigh thus in air (w). Now place the full bottle beside the specimen in the pan, and determine the joint

* *Proc. of the Royal Dublin Soc.*, vol. vi. (1888), p. 61.

† For refined work, see Berkeley, "Accurate method of determining the density of solids," *Min. Mag.*, vol. xi. (1897), p. 64.

weight, a. Transfer the specimen to the bottle, remove bubbles with particular care, replace the stopper, wipe, and weigh again (b). The weight of water displaced by the specimen $= a - b$. Then $G = \frac{w}{a - b}$.

The instrument known as **Nicholson's aræometer** or **hydrometer** is described in every text-book, and, with a delicate set of weights, gives fairly accurate results. A more or less tubular hollow metal body, closed at both ends, bears a weighted pan at the lower end, and a second pan at the upper end, supported on a thin vertical rod. The instrument floats upright in water, but must sink only so far as to leave the greater part of the rod above the surface. A scratch is made on the rod* well above the surface of the water, and weights are placed in the upper pan until this mark is brought down to the water-level. Let this weight be a. The observation is best made by looking up from below through the side of a transparent vessel, until the scratch just appears and disappears as the instrument sways slowly in the water. The specimen must be lighter than a, and is now substituted for the weights in the upper pan. Again add weights (b) until the mark comes down to the water-level. The weight of the specimen in air $(w) = a - b$. Remove the weights, and place the specimen in the lower pan. A greater weight than b will now be required to bring the instrument to the standard position. Let this weight be c; $c - b =$ the weight of the water displaced by the specimen; hence, $G = \frac{w}{c - b}$.

Undue swaying of the instrument and immersion of the weights may be prevented by covering the vessel with a card-board or wooden plate, the rod coming up through a broad slit.

Apart from the fact of its requiring a box of weights, and an inconveniently large vessel in which to float it, the aræometer scarcely competes in convenience with other simple instruments now in use.†

First among these comes an appliance resembling a steel-yard, invented by Mr. William Walker, of Dundee, and described by him in the *Geological Magazine* for 1883, p. 109. Its popularity

*This mark is generally omitted in the instruments sold, and has to be put on by the purchaser. The most accurate results are obtainable when the sinking-weight is above 15 grammes and 10 grammes or so of the specimen can be used.

† On this point see Prof. J. W. Judd, "On the rapid determination of the Specific Gravity of Minerals and Rocks." *Proc. Geol. Association*, vol. viii., p. 286.

has earned for it the name of **Walker's balance**, and it remains at present the most convenient and portable instrument of which the geologist can avail himself.

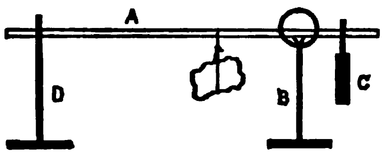

Fig. 5.

The steel bar, A, in fig. 5 is supported in the rest, B, by a knife-edge piece fixed through it about 3 inches from one end. The remainder, some 18 inches long, is graduated into inches and tenths, starting from the point of support.

The short arm of the bar is notched upon its upper surface, and a heavy weight, C, can thus be hung from it at a variety of distances from the fulcrum.

The long arm passes through a looped upright, D, which checks undue swinging, and, by a mark scratched on it, serves to indicate when the bar comes to a horizontal position.

The specimen, which may weigh several ounces, is hung by a cotton thread, a loop of which passes over the long arm. It is then slid along the arm until it counterbalances the weight C, which has been suspended near to or far from the fulcrum, according to the weight of the specimen used.

When the bar indicates by its swing that it would come to rest in a horizontal position, the reading a is taken; *i.e.*, the distance from the fulcrum of the point of suspension of the specimen.

The weight C is kept in the same position, and the specimen is immersed in a tumbler of water; to restore equilibrium, the specimen must now be carried farther out along the beam. Let this new position be b. Then, a and b being, by the principle of the lever, inversely proportional to the weights in air and water respectively, $G = \frac{b}{b - a}$.

The results are accurate to the first place of decimals, and often compete with the ordinary balance in the second place; while for mineral or rock specimens of a fair size they may be held to be entirely satisfactory.

The earlier forms of the instrument had a spare hammer-head as a weight, a shaft being also supplied. This hammer might be

used and worn down without affecting the value of the results, since all we require is that O should be the same in the two experiments made upon any one specimen. The division of the bar into centimetres and millimetres will give more delicate readings and also a useful scientific scale. The supports are made to unscrew from their bases, and all is packed away into a light box, which, for travelling, can be reduced to a baize wrapper with pockets, such as is often used for tools.*

Early in the last century, Lukens† used an equipoised beam, suspending the specimen from the shorter and thicker arm, and running a weight, which might be a smaller suspended specimen, along the other and graduated arm to restore equilibrium. Coates‡ proposed a similar beam, in which "the shorter end is undivided; but on the longer is inscribed a scale, of which every division, reckoning from the extremity of the lever, is marked with a number, which is the quotient of the length of the whole scale, divided by the distance of the division from the end. Thus at half the length is marked the number 2, at one-third 3, &c. Also at two-thirds the length is marked $1\frac{1}{2}$, at two-fifths $2\frac{1}{2}$, &c., . . . the pivot of the instrument represents unity, and a notch is made at the further end." Any convenient weight is hung by a hook from this notch, A; the specimen is slung from the other arm by a horse-hair or thread and slid along till equilibrium is attained. The reading A B, where B is the fulcrum, is obviously constant for all experiments. Immerse in water; the small weight must now be slid in from A towards the fulcrum B; let this reading in water be C B; then $G = \frac{AB}{AB - CB} = \frac{AB}{AC}$. The graduation adopted gives this result at once, for we have only to read the figure coincident with the point C.

Dr. J. Holms Pollok has independently devised a very small and portable balance on Coates's principle, which is made by Messrs. Baird & Tatlock, London, for 16s.

In Mr. R. Parish's balance,§ two pans are hung one above the other from a fixed point on one arm of the beam, the lower pan

* Walker's balance is made by Mr. G. Lowdon, Reform Street, Dundee. Price 31s. 6d.

† *Philosophical Magazine*, vol. lviii. (1821), p. 108. From *Journ. of Acad. of Nat. Sciences*, Philadelphia, vol. i., Part 2.

‡ *Ibid.*, p. 109. From same source.

§ *American Journ. of Science*, ser. iii., vol. x. (1875), p. 352.

being immersed in water. The beam is then equipoised by a small sliding weight, clamped by a screw, working on the arm that bears the pans. The specimen is laid in the upper pan, and balanced by the addition of a light pan, into which sufficient sand is thrown, suspended from the point corresponding to A in Coates's instrument. The specimen is now transferred to the lower pan, and the balancing-pan is slid inwards, care being taken not to disturb the sand. The reading now made gives the specific gravity without calculation, the graduation being on the plan employed by Coates.

One merit of this instrument is that fragmentary materials can be determined, as no suspending thread is required; but in practice it is probable that the results obtained by it are not superior to those given by Walker's balance, while it is more complicated in construction.

Prof. Jolly's spring-balance or **Federwage** is, however, simple and yields excellent results. A long brass spiral spring, which may be exchanged for one of greater delicacy if the specimen is exceptionally small, is hung from a sliding rod, set in a pedestal some 3 feet high. One end of the spring may thus be brought 5 feet above the table. The base of the instrument is pierced by three levelling-screws, and a long slip of looking-glass, with even graduations marked on it, is let into the face of the pedestal. Two light pans are hung, one below the other, from a wire hooked to the lower end of the spring, and on the wire is fixed a little bead, acting as an index.

The lower pan is sunk well in a tumbler of water, the support of which can be slid up and down the pedestal; and the sliding-rod is carried so high that the pans come to rest somewhere opposite the upper divisions on the graduated mirror. Looking along the top of the index-bead until it appears to coincide with its image in the mirror, the position of rest, a, of the spring is noted, in terms of the fine graduations used. It will be seen that this reading corresponds to the determination of the sinking-weight of the aræometer, only in this case the figure will vary according to the adjustment of the spring at starting.

Place the specimen in the upper pan, having previously drawn the tumbler to a lower position to avoid the wetting of both pans. Readjust the tumbler until the pans swing freely and as much of the lower suspending-wire is immersed as before. Take a second reading, b; then $b - a = w$, the value in air.

Transfer the specimen to the lower pan, and readjust. The new reading, c, will be less than b, and $G = \frac{w}{b - c}$.

Though not so suitable for travellers, this makes an admirable laboratory-instrument,* and, the readings being merely proportional, the utility of the spring as a weight-measurer is not affected by expansion due to change of climate.

We must conclude the present section with an account of the use of dense liquids in determining the specific gravity of mineral particles. If a solution of known density is to hand, and a specimen, though it has been completely freed from bubbles, floats upon the surface, while others sink with more or less rapidity, some idea of their relative specific gravities may be obtained.

Further, if the liquid is diluted until a particular specimen swims about in it and remains sluggishly wherever it is placed, the liquid and the mineral will be of the same specific gravity.

That of the liquid may be determined by throwing in a series of specimens already determined, until one is found that will neither float nor sink to the bottom; or by suspending a weight from a chemical or Jolly's balance, and comparing the readings given when it is immersed in water and in the liquid respectively. Prof. Sollas ("Granites of Leinster," *Transactions of the Royal Irish Academy*, vol. xxix., 1891, p. 430) has even employed a minute hydrometer.

This method of determining specific gravities, which can be used even in the case of very small specimens, was brought into prominence by Mr. E. Sonstadt † as recently as 1874, and has since been largely utilised.

Sonstadt's solution consists of a saturated solution of potassium iodide in water, in which is stirred up as much mercuric iodide as it will dissolve. "It will then dissolve more iodide of potassium, then more mercuric iodide, and so forth. The iodides dissolve very slowly at the last, and as it is best not to accelerate the solution by the application of heat, considerable time must be allowed when a liquid of maximum strength is required. The solution, after filtering, is fit for use. . . . It may be diluted to any extent, and then concentrated by heat, without injury." The maximum density obtainable falls just short of 3·2, and is about 3·17 in hot climates, these figures being higher than those first given by Sonstadt.

In addition to its use in determining specific gravities, Sonstadt pointed out that his solution would serve to separate

* Supplied by Krantz, Rheinisches Mineralien-Contor, Bonn, at 37s.

† "New Method of taking Specific Gravities," *Chemical News*, vol. xxix., p. 128.

mineral particles of one kind from others with which they might be mixed, as in the case of diamonds occurring in quartz sand. This application has been so far extended by Thoulet in France, and Goldschmidt in Germany, that the solution has often been named after these workers instead of after its original discoverer.

Rohrbach's * **solution** of iodide of mercury and iodide of barium has a density as high as 3·588, but decomposes on addition of water, and must be reduced to the density required by a specially prepared dilute solution. Neither of the foregoing liquids are satisfactory for the traveller, or even for laboratory use, on account of their dangerously corrosive and poisonous character. They have been largely superseded by the **solution of borotungstate of cadmium**, first prepared by D. Klein,† and now very widely used. This is also a pale yellow liquid, with a density of 3·28; it can be diluted with water and again concentrated by heating over a water-bath until a hornblende crystal just floats upon the surface. Any overheating will cause the salt to crystallise out on cooling down, when a fresh dilution will be necessary. Though poisonous, the borotungstate is not irritant like the mercury solutions; it can be carried about in a stoppered bottle in the solid state, and dissolved in distilled water when required. A few ready-made solutions of known density, kept carefully stoppered, will be very useful in the discrimination of gems. The only objections to this liquid are that it decomposes carbonates, so that specimens before use should be treated with a mild acid; and that it tends to crystallise readily upon the stoppers of bottles or the glass rods used in stirring. The rods and vessels used should always be washed with distilled water, the resulting very dilute solutions being kept together in a bottle, to be concentrated by evaporation when time allows.

Another liquid that is of great utility has been brought forward by R. Brauns.‡ He uses **methylene iodide**, which must be diluted with benzene and not with either water or alcohol, and which, to preserve its pale straw-colour and transparency, must be kept as much as possible from the light. When it has become darkened, as must eventually happen, the colour can be restored by putting a few globules of mercury into the bottle and

* *Neues Jahrbuch für Mineralogie, &c.*, 1883, p. 186.

† *Comptes Rendus*, tome 93; August 8, 1881. The solution, at maximum density, is sold by Marquart, of Bonn, at about £3 per kilogramme. On its manufacture, see W. Edwards, *Geol. Mag.*, 1891, p. 273.

‡ *Neues Jahrbuch für Mineralogie, &c.*, 1886, ii. Band, p. 72. The liquid is sold by chemical dealers at about 4s. per oz., three or four ounces being a fair quantity to begin with.

shaking the whole together for a few minutes. This liquid, from its not crystallising when concentrated by evaporation, is very clean and agreeable to use, but does not seem so adapted for researches made beyond the reach of laboratories as does the borotungstate of cadmium solution. Methylene iodide can be prepared of a density of 3·33, which gives it a further advantage over all but Rohrbach's solution.

J. W. Retgers has shown how methylene iodide can be raised to a density of 3·65 by dissolving iodoform in it and afterwards iodine.* He utilises for the extraction of rutile, &c., from other heavy minerals various nitrates, which become liquid at about 70° C., and are as dense as 5·0 (see p. 120).

Herr W. Muthmann † proposes the use of acetylene tetrabromide, and shows how it may be very cheaply prepared. It is diluted with benzene, or, as Mr. C. R. Lindsey informs me, still more conveniently with petroleum spirit, known commercially as "deodorised benzene." Its maximum density is 3·01.

It will be seen that the dense liquids named will serve, by proper dilution, to determine the specific gravity of most of the rock-forming minerals, though they mostly fail to discriminate between garnet and ruby, topaz and diamond, &c. It may be noted, however, that beryl will float easily in a solution in which green tourmaline sinks, while the great mass of gems can be divided off by similar observations from quartz and other worthless matter. The specimens tested should be examined with a high-power pocket-lens or a microscope in order that their purity may be guaranteed; and it is obvious that abundance of enclosures, solid or fluid, will seriously affect the results. But in practice even closely-allied felspars can be distinguished as to specific gravity by this method, which has become of increasing value with the researches of each successive year.

Undoubtedly the happiest development of the method has been the diffusion-column invented by Prof. Sollas.‡ A small test-tube, say ½ inch in diameter, is half filled with the liquid at its maximum density; water or benzene, according to the dense liquid used, is then poured on the top, no special care being necessary. The tube is set aside for twelve hours or so, by which time a column will have been produced by diffusion, the density of which increases regularly downwards. Indexes are

* *Neues Jahrb. für Min.*, &c., 1889, ii. Band, p. 185; also *Min. Mag.*, vol. ix. (1890), p. 46.

† *Zeitschrift für Krystallographie*, Bd. xxx. (1899), p. 73.

‡ *Nature*, vol. xliii. (1891), p. 404; and T. D. La Touche, *ibid.*, vol. liii., p. 199; also *ibid.*, vol. xlix., p. 211.

dropped into this, either in the form of mineral fragments of known specific gravity, or of glass beads; the latter, in coloured varieties, have a considerable range, and may have their densities determined in a diffusion-column side by side with known mineral indexes. These indexes, beads being the most convenient, float in the diffusion-column at levels corresponding to their specific gravities; hence the density of any mineral fragment dropped into a column may be found by measuring off the distance between two known indexes which lie respectively above and below it, and also measuring the distance of the mineral from one or other index. The matter is merely one of simple proportion, and the same column can be used for many fragments, and in experiments extending over several days. Mr. La Touche has devised an accurate mode of measurement, by drawing a thread horizontally across both a graduated mirror at the side of the tube and the tube itself; this thread is carried by a sliding piece of metal, fitting round the wooden support in which the test-tube is fixed. The graduated mirror is fixed vertically on the support at one side of the tube, and the position of any object in the liquid is read off by making the thread coincide with the centre of gravity of the object, the reading being given by the division cut by the thread when the eye views it as coincident with its reflection in the mirror. The note in *Nature* referred to contains figures which will show the details of construction. In many cases a millimetre-scale, held by the hand against the side of the tube, will suffice as a means of measurement.

Prof. Sollas points out that even gelatinous precipitates, if left long enough in the liquid, will lose their water and will sink to their proper level.

CHAPTER IV.

SIMPLE TESTS WITH WET REAGENTS.

The test of **solubility in water** may be important in agriculture, where mineral salts of potassium are applied to the land. The **taste** of some minerals, as rock-salt, nitre, &c., is characteristic.

The test of **solubility in acids** has been very freely applied to minerals, though with results varying according to the strength

of the acid, the temperature employed, and the time allowed for the attack. Hydrochloric and sulphuric acids are those most commonly required; nitric acid may be useful if to hand. Various forms of stoppered bottles enclosed in cases with screw-caps have been devised to meet the requirements of the traveller. It is well not to keep a small sulphuric acid bottle too well filled, on account of the highly hygroscopic character of the liquid.

The mineral to be tested should be roughly powdered and placed in a small test-tube, a few drops of acid being poured upon it. Water should be added, since solution does not always take place in the concentrated acid. The results may be noted both in cold acid and after boiling. In all cases the time of immersion in the acid and the other conditions of the experiment should be noted where comparison is desired. As these facts are rarely stated in books on mineralogy, typical and known specimens should be compared with the doubtful one under the same conditions. Should complete solution take place, further qualitative tests may be applied.

Some silicates are decomposed by boiling in hydrochloric acid, particularly those that are hydrated or with a low percentage of silica. The silica separates either in a powdery or a gelatinous condition, the jelly of silicic hydrate being often well seen after partial evaporation and cooling of the liquid. The mass clings to the test-tube, but may be removed by boiling with a strong solution of sodium carbonate.

Good examples for observing this gelatinisation are natrolite, nepheline (or elæolite), wollastonite, and ilvaite. The great majority of olivine crystals also gelatinise easily, and may be thus distinguished from pale pyroxenes, which are not decomposed.

But it must be remembered that the greater number of natural silicates are not decomposed by acids. In such cases it is necessary to determine the silica as stated on p. 63.

The commonest and most important use to which acids are put by the geologist is, however, in the examination of carbonates. A free effervescence occurs, carbon dioxide being given off, when a carbonate is placed in hydrochloric acid. The acid should be slightly diluted, and in many cases must be heated before the reaction will take place. Sulphides of certain metals, as zinc, lead, and iron, are decomposed similarly with evolution of bubbles of sulphuretted hydrogen; but, provided the mineral examined be itself free from included sulphides, there is little danger of any confusion being caused. The smell of the sulphuretted hydrogen is, moreover, noticeable, even among the fumes of the hot acid.

The use of the acid-bottle in the field itself is very limited, owing to the occurrence of dolomite and other carbonates which do not effervesce until heated. Dolomite is thus often overlooked, and some hard dolomites have even been regarded as quartzites on account of their non-effervescence in cold acid.

In 1877 Dr. H. Carrington Bolton read a paper urging the use of organic acids in the examination of minerals,* and in this and subsequent publications he has described a series of very successful experiments, showing that in particular citric, tartaric, and oxalic acids effect decompositions for which hydrochloric acid has generally been thought necessary. Citric acid may thus be carried about in a solid form, a saturated solution in cold water may be made at any time, and the ordinary tests for the presence of carbon dioxide, or sulphur in certain sulphides, may be performed with this, hot or cold, in a test-tube. Some silicates are decomposable, with or without gelatinisation, and in many cases the solution does not require to be heated. Ordinarily a rather longer time must be allowed for the action of the acid than is the case with hydrochloric acid.

Dr. Bolton has tabulated his results with citric acid, which is the most useful reagent;† he employs also a boiling solution of citric acid to which sodium nitrate is added, and imitates the reactions of hydrochloric acid by introducing iodine in the form of potassium iodide, which is decomposed by the hot citric acid.‡ The value of these results obviously consists in the fact that the reagents are solid, and are dissolved only as required.

From the series of minerals examined we may quote the following:—

Decomposed in Fine Powder by a Saturated Solution of Citric Acid.

A. *Without evolution of gas.*—Brucite (cold solution). Gypsum (on boiling).

B. *With evolution of carbon dioxide.*—Calcite and aragonite easily in cold solution; dolomite and ankerite far less easily; chalybite and magnesite only on boiling. It must be noted in testing for carbonates with hot citric acid that the oxides of manganese (hausmannite, pyrolusite, manganite, psilo-

* "Application of Organic Acids to the Examination of Minerals," *Annals New York Acad. of Sciences*, vol. i. (1879), p. 1. See for this and later work *Chemical News*, vols. xxxvi., xxxvii., and xliii.

† *Chemical News*, vol. xliii. (1881), p. 40.

‡ See also *Chemical News*, vol. xxxviii. (1878), p. 169.

melane, and wad) evolve carbon dioxide by decomposition of the citric acid; but the character of these minerals is not likely to allow of confusion with carbonates.

C. *With evolution of sulphuretted hydrogen.*—Galena, zinc-blende, and pyrrhotine, in cold solution. Iron pyrites resists until boiled with citric acid and sodium nitrate, when it readily decomposes, whether in the cubic or rhombic (marcasite) form. Copper pyrites requires similar treatment.

D. *With separation of silica.*—Nepheline, analcime, stilbite, and wollastonite yield silica in a cold solution (long standing is desirable), becoming partially decomposed; natrolite and hemimorphite are decomposed with gelatinisation. Serpentine and ilvaite are decomposed only on boiling, without gelatinisation.

Olivine, augite, epidote, almandine, and hornblende (slightly) have been decomposed by boiling the solution and adding potassium iodide.

E. Among the *minerals that are not decomposed* by the above attacks, we may quote diopside, asbestos, zircon, idocrase, zoisite, the micas, leucite, sphene, talc, the felspars, barytes, celestine, and anhydrite.

In testing for ordinary limestones in the field itself we find that a little of the powdered citric acid may be shaken from a tube upon the rock-surface; an area about an eighth of an inch square is ample for the purpose, though of course the test should be applied to different portions of the same mass. The addition of a drop of water produces almost immediate effervescence if the material is truly calcite. The bubbles formed can be observed with the lens or the eye alone. In the case of loose friable rocks such as chalk the reaction is very brisk; but with crystalline marbles a minute or so should be allowed. It is clear that in rough hill-work it is better to carry a flask of water and the dry citric acid than to risk the fracture of a bottle of hydrochloric acid in the pocket.

Just as, by the aid of the blowpipe, the geologist is accustomed to perform many qualitative operations with a very limited supply of material, so a number of wet reactions familiar to the chemist may be repeated upon quite a microscopic scale (see Apatite, p. 67). Decomposable compounds of calcium may thus be treated with hydrochloric acid upon a microscopic slide; the addition of a drop of sulphuric acid to the solution throws down crystals of gypsum in radial bunches or still more characteristic forms, which can be examined at once under the microscope. Microchemistry has, indeed, become a special study, and will greatly facilitate the determination of the minute fragments

with which a geologist is often called upon to deal. But for detailed accounts of the various methods put forward, the student may best refer to *A Manual of Microchemical Analysis*, by Prof. H. Behrens, with historical introduction and references to previous literature, by Prof. Judd (Macmillan & Co., 1894). Many of the processes are rendered more difficult than would at first appear by the great care that must be taken as to the purity of the reagents used.

Two tests of especial advantage to geologists have been introduced by Messrs. Meigen and Lemberg respectively. The former* distinguishes aragonite from calcite by boiling the powdered mineral for a few minutes in a dilute solution of cobalt nitrate. Aragonite precipitates lilac-red basic cobalt carbonate, while calcite remains white, or turns yellowish if organic matter is present. Witherite and strontianite behave like aragonite; magnesite gives no reaction. Apatite gives a blue precipitate.

Lemberg† dissolves 4 parts of aluminium chloride in 60 parts of water, and adds 6 parts of dry logwood. Digest and stir for 25 minutes. Filter the solution thus produced, which is coloured a rich violet by the hæmatoxylin. Small fragments of calcite left for six or seven minutes in this solution, and then washed with water, are seen to have become violet, through the deposition of aluminium hydrate, which takes up the hæmatoxylin dye. Dolomite, on the other hand, remains colourless, and, even after ten minutes, shows only a few blue spots. Brucite remains similarly very little altered.

* *Centralblatt für Min.*, &c., 1901, p. 577.
† *Zeitschrift der deutsch. geol. Gesell.*, Bd. xi. (1888), p. 357.

CHAPTER V.

EXAMINATION OF MINERALS WITH THE BLOWPIPE.

I. Apparatus and Reagents.

No geologist can consider himself equipped for determinative observations until he has systematically examined a series of typical minerals with the blowpipe and with associated tests. The instruments and reagents required are few and simple, and may be had from chemical dealers packed into boxes of very moderate size. For purely qualitative determinations, such as are here described, the following apparatus will probably be found sufficient:—

A. Apparatus.

Blowpipe.—Black's form in brass, with its conical tube, or preferably Plattner's, in which the parts are usually better made; both are convenient instruments. Some workers prefer an expanded mouthpiece to the ordinary tubular one of bone; but this is much a matter of opinion. The nozzle is far more important than the mouthpiece, and its aperture should be cleanly circular and not too large. As sold, this generally requires adjustment. The end of the nozzle, whether brass or platinum, should be slightly hammered over, so as to contract the aperture; this should again be enlarged by thrusting a large pin or needle through it, any metal projecting outwards being removed with a file. Examine with the lens, and repeat the operation until a perfectly circular opening is produced. The size may vary with individual requirements, but probably few workers will need an aperture larger than this dot (•).

A platinum nozzle, costing about three shillings extra, may be added to any blowpipe, and, besides being clean, can never cause colouration in the flame.

Lamps.—Blowpipe-lamps are so convenient, being unencumbered with tubes or taps, that the use of gas in such work is a very questionable luxury. Where, however, gas is obtainable, the ordinary Bunsen-burner serves all purposes. The air being admitted below, it provides a clean flame for the heating of glass tubes and for observing the colouration due to volatile oxides; with the air-holes closed, and the flame reduced to about 1½ inches in height, it gives a luminous cone that can easily be manipulated by the blowpipe.

A brass tube, flattened at the top and cut off obliquely (fig. 6), should be dropped into the ordinary Bunsen-tube from above, preventing the access of air by surrounding the jet where the gas enters, and at the same time giving a flattened flame above, the blowpipe being directed along the slit-like opening.

Fig. 6.

Where gas cannot be had, any simple spirit-lamp, or the colourless blowpipe-flame, will serve for boiling specimens in acid, &c. The blowpipe-lamp may burn oil, and be provided with a screw-cap for travelling. The wick should be flat. A small-sized cyclist's head-lamp is not unsuitable, as, in its ordinary case, it can be kept upright and utilised as a lantern. Olive or refined colza oil is recommended for blowpipe work. By far the best lamps, however, where space is limited and things have to be easily stowed away, are those filled with grease or solid paraffin. A little cylindrical box of tin has a wick-holder soldered on one side, through which a flattened wick is drawn. The box is then filled by melting down old candle-ends, or in any other convenient way according to the materials available. When brought into use, the wick is lighted and the flame directed with the blowpipe upon the surface of the solid tallow, until this is melted to a depth of about a quarter of an inch. The lamp will then become hot enough during use for a continuous supply to be maintained; but it is still better to hold the lamp with the pliers over the spirit-lamp until all the contents become fluid. When about half or three-quarters empty, it is well to drop in extra lumps of fuel—a single candle-end or so—during use, and this additional material becomes melted up slowly with the rest. The wick must be freely supplied with fluid fuel, or it will char and waste away. If the lamp is kept sufficiently hot, the wick will not require raising during a day's work; but it can easily be thrust up with a knife-point after the flame has been at work for a few minutes.

A cylindrical cap fits down upon the lamp when put aside,

and serves also as a stand for it, a little stop projecting from the side of the lamp and catching on the edge of the inverted cover (fig. 7).* More elaborate forms of lamp upon the same principle have been constructed by various makers.

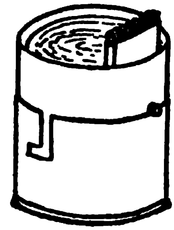

Fig. 7.

In the matter of combustibles, Mr. Attwood makes a valuable suggestion (*Practical Blowpipe Assaying*, p. 7):—"In some countries—the interior of South America, for instance—alcohol cannot be procured except at a great cost; but as crude spirits made from sugar-cane, &c., are generally plentiful in such places, they afford the explorer a good substitute for alcohol as well as oil, owing to the presence of more carbon than pure alcohol contains. The spirits, however, contain some water; and after the fuel is about one-half consumed it is best to empty the lamp and fill again with fresh spirits." †

Platinum Wire.—Twelve inches or so of wire should be kept on hand if much work is undertaken, as it is liable to suffer from the formation of fusible alloys. It should not be so thin as to tremble in the hand, nor yet thicker than this line ——, so that it may not conduct away the heat too freely from an assay supported on it. One end may be twisted round in a coil to serve as a handle, or pieces 5 centimetres or so long may be fused into handles made of glass rod.

A strip or two of **platinum foil**, 5 centimetres by 2, may be at times useful as a support during fusions; and a spoon of the same metal, like a tiny crucible, which can be held in the forceps by a projecting tongue, forms a handy accessory, though a luxury. If the platinum, after use, does not become cleaned by hot water or acid, a little bisulphate of potash should be fused upon it, and dissolved off in hot water, leaving a perfectly clean surface.

Charcoal.—This is used as a support for assays and as a reagent for their reduction. If ordinary charred wood is used, it should be cut into convenient prisms some 10 centimetres long, with a section 5 cm. square. It should give little ash, and should not be liable to split and crack suddenly during heating. Pine wood is preferred. The best supports are made by rubbing up finely-powdered charcoal in a mortar with fairly thin starch paste, made with boiling water, until a stiff mass results. This can be moulded before drying into any suitable shape. The support,

* This simple lamp is supplied with the blowpipe-cabinets of J. T. Letcher, Truro (or Baird & Tatlock, London), and is sold separately for 10d.

† Excellent work can be done with an ordinary candle, especially if the flame is directed horizontally, and not down upon the tallow.

when dry, is heated just to redness in a crucible, to char the starch cement.

Good blocks prepared in this way, and of the size above given, can be purchased of chemical dealers. Small cup-like supports, which are sometimes called "pastilles," can be made by pressing the material with a round-ended stick into a basin-shaped hollow, about 2 cm. in diameter, cut in a block of wood. Plattner recommends that both the mould and stamp should be rubbed over with charcoal dust, and that a strip of paper be laid in the mould to facilitate the removal of the cup when made. The little charcoals thus prepared can be easily dried and ignited, and can be supported in the flame on a ring of stout wire when finally brought into use. Where, however, encrustations have to be looked for, forming at any distance from the assay, a prolongation of the charcoal is required, on the cool surface of which they may be deposited. Thus in the case of arsenic it is well to have several inches of charcoal beyond the point where the specimen is being heated. The long blocks already mentioned are here of advantage; but a support of unglazed porcelain is sometimes used, the "pastille" being placed in a depression at one end of its upper surface. This surface is smoked over by the flame of the lamp, and serves admirably to receive the encrustations. The great advantage of this method is that any reagents absorbed cannot contaminate the charcoal used in subsequent work. The little cup is thrown away when done with, and a clean one set in its place. Larger charcoals must be cut or filed away until a reliably clean surface is restored.

Ross's **aluminium plate**, 10 cm. by 5 cm., and 1 mm. thick, is also used as a support, the lower end being turned up at an angle of 80° to carry the little charcoal, and the longer part receiving the sublimate. Many of the encrustations thus seen are far more vivid than on the surface of charcoal. The plate can be cleaned with a wash-leather, bone-ash, and water.*

Forceps.—A pair of steel forceps with platinum points is practically indispensable, so made as to be self-closing. A light pressure on the sides, at some distance from the heated end, should suffice to separate the points. Splinters are held in these when fusibility is being tested; but metallic-looking substances, or any suspected of containing arsenic, antimony, lead, zinc, or bismuth, should never be heated in the forceps, lest the platinum tips should become fused. Small glass tubes can generally be gripped by such forceps when placed behind the platinum points.

Magnet.—Any small bar form.

Anvil and Hammer, or Steel Crushing-Mortar.—A little square

* Dr. Haanel has used plaster of Paris plates, the advantages of which are described on p. 55.

anvil of polished steel and a light steel hammer are required for breaking up minerals prior to the transference of the particles to the agate mortar for final grinding. A cylindrical steel mortar with accurately fitting pestle is of course still more convenient; but most cases of difficulty are met by the arrangement supplied with Letcher's blowpipe-cabinets. The mineral fragment is laid upon the anvil; a little steel ring, about 7 millimetres deep, is placed round it, corresponding to the wall of the crushing-mortar; and a cylindrical pestle, fitting into this, is hammered down upon it.

Agate Mortar and Pestle.—A good size is 5 cm. in diameter. The pestle may be mounted in a wooden handle, as the agate itself is likely to be small for the hand.

Pliers.—Steel pliers are often useful for detaching fragments from specimens where the blow of a hammer would be disastrous. A cutting edge is also of value.

File.—A small file, triangular in section, is required to cut up glass tubing and for certain observations on hardness.

Glass Tubing.—This is sold by the pound, and should have a bore of about 5 millimetres. It should not yield too easily to the flame. It is cut up into pieces some 12 cm. long, by notching it with the file and then breaking it across. Some of these pieces are kept as open tubes. To make closed tubes, hold one end of an open tube in each hand, and bring the centre into a Bunsen-flame or that of a spirit-lamp. When this part is thoroughly softened by the heat, draw apart the two ends, and two fairly regular closed tubes will result. The closed ends of these must not be knotty or thickened, or they will crack on being again brought into the flame. It is seldom worth while to spend much time in the elaboration of a bulb on a closed tube, since a heavy sublimate or the fusion of the assay into the glass will render it useless for other experiments.

Glass Rod.—A few pieces, of a size that will fit down into the tubing. The ends should be rounded in the Bunsen or blowpipe flame.

Test-tubes.—Taste differs as to the size of these, but 1 cm. is an ample diameter. In the absence of a proper stand, they can always be kept upright in a gallipot or wide-mouthed bottle. They are used for tests with wet reagents.

Watch-glasses.—In the absence of these, circular palettes from a colour-box are useful. Reactions with wet reagents, where the behaviour of the mineral particle has to be observed, are often best conducted in these vessels. They serve also as clean receptacles for specimens and reagents that are set out for

immediate use. A cheap double concave lens is rather an improvement upon the ordinary watch-glass, since it will stand firmly, and either surface can be used.

Porcelain Dishes.—Two or three, about 3 cm. in diameter and fairly deep, made to resist heat. They should stand without support, and are invaluable for treating minerals either in boiling or cold acid. For travelling they are far superior to beakers.

Blue Glass.—Three 2-inch squares of cobalt glass, of different thicknesses, are required for observing some flame-colourations. A wooden block of sufficient height, with a groove at the top, will support the glass between the eye and the flame, and leave both hands of the operator free.

B. Reagents.

Borax.—Powdered crystals.

Microcosmic Salt (hydrogen sodium ammonium phosphate).—Powdered crystals. These two dry reagents are used as fluxes on platinum wire, characteristic colours being imparted by many metallic oxides to the glass formed on fusion.

Carbonate of Soda.—Powdered crystals of the dry carbonate. They must be free from sulphur (see Sulphur test, p. 57). Used to effect fusions and reductions on charcoal, and as a test for manganese.

Nitrate of Cobalt.—A solution of the crystals in 10 parts of water, kept in a stoppered bottle. Drops can be taken out with a glass rod or a tube drawn out as a pipette; or a little glass bulb can be made, with a narrow neck. This bulb is heated and the neck placed beneath the solution, a little of which enters; on reheating, so as to convert the water present into steam, and again immersing the neck, the bulb becomes nearly filled. When held inverted in the hand, the air within expands and forces out the liquid in convenient drops (Brush, *Determinative Mineralogy*).

Hydrochloric Acid.—Concentrated, in stoppered bottle.

Sulphuric Acid.—Concentrated, in stoppered bottle. Dilution must be performed carefully, owing to the heat evolved.

In use, a little of each of these acids must be poured out into watch-glasses or beakers, since wires, &c., have to be dipped in them, and the main store in the bottle must be left absolutely uncontaminated. This precaution is very simple, but a warning on the point is often necessary.

Tin-foil.—Used to facilitate many reductions, both in borax and in hydrochloric acid.

Copper Wire (some workers use cupric oxide).—Used in testing for chlorine, owing to its combination with the copper and the colour consequently imparted to the flame.

The following reagents are less important:—

Potassium Bisulphate ($KHSO_4$).—Powdered crystals in stoppered bottle. Used in some fusions.

Fluor-spar.—Powdered. Mixed with the above in testing for boron in the flame, but of doubtful value.

Magnesium.—The ordinary magnesium tape or wire. Used in testing for phosphorus.

Potassium Iodide and Sulphur.—A mixture of equal parts. Used on charcoal in discriminating between the encrustations due to lead and bismuth.

Silver Chloride.—Used to intensify some flame-colourations.

Gold.—In small beads. For determining nickel in presence of cobalt.

Nitric Acid.—In stoppered bottle.

Ammonium Molybdate.—Dissolved in ammonia and added to dilute nitric acid. Fresenius gives the proportions:—Ammonium molybdate, 10 grms.; ammonia, sp. gr. ·96, 40 cc.; strong nitric acid, 80 cc.; water, 80 cc. For detection of phosphates.

Bone-ash.—For use in cupellation (p. 56).

Fuel for the lamps must not be neglected when travelling.

C. Works on Blowpipe-Analysis.

G. Attwood. Practical Blowpipe Assaying. Sampson Low & Co., 1880.

G. J. Brush. Manual of Determinative Mineralogy. Wiley & Sons, New York; Chapman & Hall, London. 16th edition, 1905. (A remarkably clear, concise, and valuable work, now without a rival.)

Von Kobell. Les Minéraux (French edition by Pisani). Rothschild, Paris, 1879. (A book for the pocket, embodying much information.)

Plattner. Qualitative and Quantitative Analysis with the Blowpipe. Edited by Richter and Cookesley. Chatto & Windus, London, 1875.

W. A. Ross. Manual of Blowpipe Analysis. Sampson Low & Co., 1880.

II. Blowpipe-Operations.

A. Production of the Blowpipe-Flame.

Distend the cheeks and breathe in and out as usual by the nose. Now place the blowpipe between the lips, or the trumpet mouthpiece against them. Some of the expired air will pass out

by the tube, under pressure from the tension of the cheeks, and the remainder will pass out through the nose. At short intervals the cheeks must be re-distended in order to maintain the pressure. In this way a continuous blast can be kept up without interfering with the ordinary action of the lungs. Practice is all that is necessary; most of the difficulties that at first occur are caused by the endeavour to force all the expired air out through the blowpipe instead of by its natural exit, and by allowing the cheeks to fall in too far, so that a sudden distension becomes necessary and the blast is momentarily checked.

It is necessary in some reductions to maintain a blast for two to three minutes, but seldom longer, and, when the habit is once acquired, time makes little difference; but saliva is apt to accumulate in the bottom of the blowpipe during long blowing, and the expanded part there must occasionally be emptied. In Fletcher's hot-blast blowpipe, where the tube bearing the nozzle is coiled round so as to become heated above it in the upper part of the flame, all moisture is converted into steam before it can reach the orifice. This form of blowpipe is particularly adapted for effecting fusions and oxidations, but the hot surface of the tube is sometimes an inconvenience when laid upon the table.

For persons whose breathing is in any way affected, a hand-bellows may be necessary, such as that made by Fletcher of Warrington, which is a reproduction in miniature of the well-known foot-bellows, and gives a good continuous blast. But for travelling purposes and allowing the operator every delicacy of control over the flame there is little doubt that the mouth-blowpipe is the best.

When the blast can be produced without effort, place the nozzle just outside the flame of the lamp, directed along the wick or the slit-like orifice of the gas-burner, and almost resting upon it. The flame should be about 1½ inches high above the burner. Blowing somewhat gently, so as not to force in too

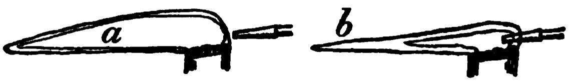

Fig. 8.

much air, the flame will be carried out sideways, preserving in part its luminous character. It may be broadly regarded, in fact, as a luminous inner cone (*a*, fig. 8) surrounded by a thin envelope of more highly heated and oxidised matter. A body

placed well within *a* is cut off from contact with the outer air, and yet, if brought near the point, becomes highly heated. The result is its *reduction*, the glowing carbon by which it is surrounded largely assisting in the removal of any oxygen it may contain, although the heat must be sufficient to prevent the deposition of soot upon it. The flame thus produced is the **Reducing Flame**, designated by long tradition by the letters **R. F.**

Next place the nozzle some little distance inside the lamp-flame and blow more strongly. The luminous cone is shortened and almost disappears, enough air being supplied to effect the oxidation of the glowing carbon compounds. The outer envelope now assumes importance, forming a long almost invisible cone (*b*, fig. 8), which is the **Oxidising Flame, or O. F.** A body placed at the point of this, or, if the heat is sufficiently strong, out beyond its visible termination, becomes heated in contact with the air, and consequently takes up oxygen according to its affinities. The flame must be hot enough to dissociate most sulphides, which become thus converted into oxides. Such a process is known as "roasting." *

If mere heat is required, as in the determination of fusibility, the nozzle is placed as in the production of the oxidising flame, but the substance is held inside the blue point of the visible flame, since here the highest temperature occurs. This position may be styled the **Fusion-place** (below the *b* in fig. 8).

B. Observation of Fusibility.

The ease with which a substance fuses must depend greatly on the strength of flame employed and on the skill of the operator, as well as on the size of the fragment employed. Hence it is necessary for each worker to be in the habit of using splinters of similar size and shape, comparison being then possible between the results gained by himself from different substances. The product, after heating, must always be examined with the lens, and any change of colour, transparency, &c., also noted. For most purposes, the following broad observations and statements suffice:—(*a.*) Fusible in the unaided flame of the lamp in fairly large (or small) fragments; (*b.*) fusible before the blowpipe (*b* B) with easy formation of a globule; (*c.*) fusible *b* B with easy rounding of the edges; (*d.*) fusible *b* B in splinters only; (*e.*)

* To test the R. F. a borax bead strongly coloured with manganese should be rendered colourless; in a good O. F. a borax bead containing much molybdenum should also become colourless (see p. 51).

fusible *b* B on the edges of thin splinters only; (*f*.) infusible *b* B, even after prolonged heating. The specimens are held in the flame in the platinum forceps or in a tiny loop of platinum wire, through which a wedge-shaped splinter may be slung. The fusion-place is used. To facilitate comparison with typical minerals, von Kobell proposed the well-known Scale of Fusibility. The six degrees are formed by:—

1. Antimonite (the most easily fusible member of the scale).
2. Natrolite.
3. Almandine (common) Garnet.
4. Actinolite.
5. Orthoclase.
6. Bronzite.

A good blowpipe-flame should fuse the tips of thin splinters of bronzite into tiny globules. Degrees 1, 2, and 3 correspond respectively to the verbal descriptions *a*, *b*, and *c*, given above; 4 and 5 to *d*; and 6 to *e*.

Dr. Joly, working with his beautiful "meldometer," has criticised this scale when applied to *powdered* minerals; and it no doubt stands in the same position as the scale of hardness, with its highly irregular intervals (*Proc. R. Irish Acad.*, ser. 3, vol. ii., p. 39).

It must be remembered that the substances styled by the mineralogist infusible are mostly fusible with ease in the flame of the oxyhydrogen blowpipe.

H. B. de Saussure * made a number of determinations, nearly a century ago, of the fusibility of minerals in minute grains. As a support he used a little splinter of the infusible mineral kyanite, which was fixed in a glass tube by fusion of the latter. He moistened the fibrous end of this splinter with saliva or slightly gummy water, and picked up several granules to be tested at a time, since some would be apt to fly off at first contact with the flame. He examined the product of fusion with the microscope, and claims to have fused a fragment of rock-crystal ·005 of a line in diameter and ·06 of a line long by the use of a stout candle and a blowpipe supplied with ordinary air. He compared the diameters of the globules that he could produce by the fusion of various minerals and of the members of Wedgwood's pyrometric scale, being driven to these minute experiments by the dearness of combustibles in his city. Finding that some bodies, such as calcite, gypsum, and fluor-spar, acted on and destroyed the kyanite, he supported these on a

* "Nouvelles recherches sur l'usage du chalumeau dans la Minéralogie," *Journ. de Physique*, t. xlv. (1794). p. 3.

splinter broken from the specimen under examination. He proposed, however, to study the interaction of one mineral on another by using a support of the one and a granule of the other. Cordier subsequently utilised this method by fusing two grains of different kinds placed in contact on the kyanite support.

Though the elaborate detail with which the comparisons of De Saussure were carried out proved an obstacle to the development of his method, Cordier speaks very highly of it as a means of studying small isolated grains. We refer to it here as an example of the practice of the earlier observers, and as an encouragement to those who may regard the possession of platinum wire and a Bunsen-burner as a necessity rather than as a luxury in determinative work.

Dr. C. Dölter,* working with Le Chatelier's pyrometer, shows that most rock-forming minerals fuse between 1000° and 1300°. A. Brun† gives 1200° to 1900° for common silicates.

C. Observation of Flame-Colouration.

Many volatile substances impart characteristic colours to the flame. The observation should be coupled with that of fusibility, but a negative result is not conclusive. Should no colour be thus seen, the splinter, or its powder on a moistened wire, should be dipped in a drop of hydrochloric acid specially placed out for this purpose, and again be introduced into the flame.

Compounds of phosphorus and boron are best treated with sulphuric acid. Silver chloride, mixed with the powder of the specimen, is useful to intensify some reactions, notably those of copper compounds, the blue flame due to copper chloride becoming at once apparent. Gypsum may similarly be used with certain silicates, which become decomposed when heated with it, the metals present being rendered volatile in the form of sulphates.

Often the assay must be held just in the edge of the flame, and not brought too far within it. The colouration is sometimes transient, sometimes intensified upon long heating or fusion. When a Bunsen-burner is used, the colours are better seen, the assay being held on platinum wire or in the forceps near the base of the flame and at its margin. Often a little of

* *Tschermak's Mitt.*, Bd. xx. (1901), p. 210.

† *Arch. Sci. phys. et nat. de Genève*, 4e. sér., t. xiii., p. 352.

the powder scattered through the flame gives an unmistakable reaction.

Precautions.—A black background, such as a charcoal block or a book-cover, should be used, lest faint-green and blue colourations should be overlooked.

The forceps or wire must give no colour when held alone in the flame. They can be cleaned by dipping in hydrochloric acid and heating until they have no effect on the flame.

The acids used must give no colour, beyond, perhaps, the transient yellow of sodium, which is scarcely to be avoided. The wire must never be dipped into the acid-bottle, but drops must be set out for use.

When a Bunsen-burner is used, the table must not be jarred nor the brass tube touched or disturbed, since the large surface of the flame at once becomes coloured by foreign bodies thus projected into it.

The flame-colourations to be looked for are as follows—those given by rare substances being omitted as foreign to the practical purpose of this book. The metal indicated by the reaction is given in *italics* after each :—

Crimson, approaching Purple. *Lithium.*—Appears when the assay is on the very margin of the flame.

Crimson, of Yellower Tinge. *Strontium.*

Red to Yellow-Red. *Calcium.*—Often similar to that of strontium, other tests distinguishing the compounds of these metals.

Yellow. *Sodium.*—So prevalent that a strong persistent flame can alone be regarded as satisfactory evidence of its presence as an essential constituent of the assay.

Yellow-Green. *Barium* or *Molybdenum.*

Bright Emerald Green. *Copper.*—A blue inner flame appears when hydrochloric acid has been used.

Bright Green. *Boron.*—Appears when the assay is on the very margin of the flame. Sulphuric acid must be used. Borax is a good example.

Dull Green, inconspicuous. *Phosphorus.*—Sulphuric acid should be used, and the flame carefully observed on the entrance of the assay.

Bluish-Green. *Antimony* (often smoky). *Tellurium* (rare).

Blue. *Lead, Selenium* (rare), or *Copper Chloride.*—The last gives the green of the oxide beyond and round it. (See "Chlorine," p. 61.)

Light Blue, smoky. *Arsenic.*

Violet. *Potassium.*—This flame is very easily masked by sodium, and entails in most cases the use of the blue glass. Where potassium is suspected, a blue glass, or a combination of glasses, is selected, that will cut off the purple tints given by a strong sodium flame, such as can be made for trial with sodium carbonate. The glasses commonly supplied are far too thin; 5 mm. is a good thickness. The glass is then held between the eye and the flame that is to be tested, and the reddish-violet tinge due to potassium may be observed through it, particularly when the assay has become thoroughly heated. If lithium is also present, the colouration due to it may be transmitted, but can be cut off by a comparatively small thickness of blue glass. In ordinary work no confusion is likely to result, potassium being far more prominent in the minerals commonly met with by geologists. For the intensification of potassium flames by gypsum or sodium carbonate, see pp. 83, 85.

Finally, some minerals may give double flames, as pyromorphite, which shows a blue flame surrounded by a green envelope; or borax, which reveals sodium when heated alone, and the green of boron with sulphuric acid.

D. Reactions in Beads of Borax.

Shake out a little borax into a watch-glass. Bend one end of a clean platinum wire into a small loop not larger than this, O, heat it, and dip it in the borax, some of which will fuse and adhere to it. On further heating, the borax will swell up, fuse, and settle down on the loop as a clear globule. Let this cool and hold it up to the light; if any colouration is visible in the bead thus made, the wire must have been insufficiently cleaned. A light blow between the hammer and anvil will break out the bead; a new one must be formed and shaken off when hot, probably carrying with it any residual impurities. The third bead now made will be perfectly colourless.

After inspecting the bead, fuse it again and take up a small quantity of the powdered assay, by touching it with the hot bead. Heat in the oxidising flame in full contact with the air for about the time occupied in counting fifty distinctly; then remove it and hold it up to the light. Note, after the first red glow has gone off, any colour while hot, and whether any change takes

place on cooling. Write the result on paper for reference as the reactions accumulate.

Now place the same bead in the reducing flame and heat for at least as long a time. The practice of silently counting during such operations is a useful one, as ensuring a fair similarity of conditions in examining different substances, and as a check to careless hurry. The results when hot, cooling, and cold should again be noted.

If any doubt remains, the bead can be again oxidised and re-examined. If the reaction is feeble, more powder must be added; if the bead is dark and opaque, it can be flattened out when still hot between the agate pestle and the edge of the mortar, when it frequently becomes transparent. If clearly too much material has been picked up, part of the bead must be shaken off when hot and pure borax substituted.

As already hinted, compounds of arsenic, antimony, lead, &c., will destroy the wire, and in some cases the bead must be treated in a little hollow of a charcoal support; it must then be pinched up while hot, and its colour thus examined. The addition of tin aids some difficult reactions in R.F. The bead is fused on charcoal, and the corner of a strip of tin-foil is dipped into it, a little being thus melted off. The tin combines with the oxygen of other metals present, and the reduction is carried farther than by the flame alone.

Two or even more metals capable of colouring the borax glass may exist in the same assay. Hence the worker must be prepared for mixed colours, such as a green in the case of cobalt and iron, &c. Such colours are particularly noticeable in the hot bead, as also are those due to constituents present in small quantity.

Precautions.—The wire must be clean and give no colour to the pure borax.

The bead must be small, so as to be completely enveloped during reduction.

The powdered assay must be added in small quantity, and increased until it is clear that no good reaction is obtainable.

Sulphides and arsenides should be roasted on charcoal before use in borax.

The reactions that are commonly met with and can be fully relied on are here given. Many substances give beads that are yellow when hot and colourless when cold, or make opaque porcellanous beads when added in large quantity; but their constituents can usually be recognised by other and better means.

BEADS OF BORAX.

Colour in O.F.	Colour in R.F.	Indication.
Brown (Violet when hot).	**Greyish** on long reduction. Colourless with tin.	*Nickel.*
Yellow (Red when hot).	**Bottle-green.**	*Iron* or *Uranium.*
Yellow-green.	**Green.**	*Chromium.*
Blue (Green hot, and, if a large quantity is used, when cold).	**Brick-red** and opaque. Well seen in yellow light of lamp. Facilitated by tin, or when a large quantity is present.	*Copper.*
Blue.	**Blue.**	*Cobalt.*
Red-violet.	**Colourless** (difficult with large quantity).	*Manganese.*
Colourless (requires good oxidation).	**Brown,** often with black flecks.	*Molybdenum.*
Colourless.	**Yellow-brown** with large quantity.	*Tungsten.*
Colourless (Yellow hot).	**Yellow** to **Brown.**	*Titanium.*
White and opaque (turbid with small quantity).	**Colourless** after some time.	*Silver.*

E. Reactions in Beads of Microcosmic Salt.

It is always advisable to confirm the results obtained in borax by the use of microcosmic salt, and in many cases, as where uranium, iron, titanium, or tungsten occur, these reactions are absolutely necessary. While a larger quantity of the mineral powder is often required before a good result is obtained, the reactions are as a whole cleaner and clearer than those in borax. The opaque red of copper in R. F. is, moreover, easily produced in microcosmic salt.

The salt must be picked up on the heated wire in small quantities at a time, and fused so as to expel the water and ammonia after each addition. The resulting bead drops easily from the wire, but any tendency to fall during an operation may be generally checked by shifting the wire to the upper portion of the flame.

Precautions.—The bead must be small and be moved with care, lest it should become detached.

Larger quantities of the assay may possibly be required than in the experiments with borax.

The other precautions are the same as those given under borax.

BEADS OF MICROCOSMIC SALT.

COLOUR IN O.F.	COLOUR IN R.F.	INDICATION.
Yellow.	Yellow (colourless after long reduction with Tin).	*Nickel.*
Pinkish-red (requires some quantity).	Pinkish-red (requires some quantity).	*Iron.*
Pinkish-red (requires some quantity).	Darker or Crimson-red.	*Tungsten and Iron*, or *Titanium and Iron.*
Yellow-green.	Green.	*Uranium.*
Yellow-green (Red when hot).	Green (Red when hot).	*Chromium.*
Blue.	Red and opaque.	*Copper.*
Blue; sometimes Violet.*	Blue; sometimes Violet.	*Cobalt.*
Red-violet.	Colourless (easier than in Borax).	*Manganese.*
Green; rarely Colourless.	Green.	*Molybdenum.*
Colourless.	Blue.	*Tungsten* (see above for Tungsten and Iron).
Colourless.	Violet.	*Titanium* (see above for Titanium and Iron).
Milky-white and turbid.	Colourless (after some time).	*Silver.*

F. EXAMINATION FOR SILICA IN BEAD OF MICROCOSMIC SALT.

If a minute splinter of a silicate is placed in the bead and heated thus for a long period, the silica will still remain undissolved, and will be seen floating about as a skeleton retaining the form of the original fragment. Some substances, as corundum, rutile, &c., are so slowly soluble that this test must be performed with judgment,

* Some samples of microcosmic salt give violet beads.

and upon particles not bigger than the commas used upon this page. At least 200 should be counted during the operation.

In borax, on the other hand, silica eventually dissolves, in common with the bases combined with it. A small portion of the silica is said to be dissolved out even in the bead of microcosmic salt, but this does not vitiate the observation unless a fine powder has been used in place of a properly selected splinter.

G. Reactions in the Glass Tubes.

A closed tube, prepared as described on p. 41, and dried in the flame, is held in the forceps or any convenient clip, and two or three fragments of the mineral are dropped into it. No powder should be allowed to fall upon the sides of the tube, lest sublimates should be obscured. The base of the tube is heated, gently at first, in the spirit-lamp or Bunsen-flame, the blowpipe being used if greater heat seems desirable. Any change that takes place should at once be noted; decrepitation, fusion, change of colour, &c., may occur; but the most important reactions are the evolution of gas and the formation of a sublimate in the cooler part of the tube. The assay may in some few cases become thus entirely volatilised; but a residue commonly occurs, which should be examined; occasionally this proves to be magnetic.

A tube should then be taken that is open at both ends, and about 12 cm. long. A fragment of the mineral is shaken in so as to lie about 2 cm. from one end, and the flame is allowed to play about this point. By inclining the tube, air-currents pass up it of strength varying with the slope, and the volatile matter, if any, becomes highly oxidised. Gases and sublimates should again be closely observed.

It is clear that sulphides will be most likely to yield sulphur in the closed tube, the product in the open tube being sulphurous anhydride (SO_2), an invisible gas characterised by its smell. Arsenic may appear as a metallic sublimate in the closed tube, but as a white oxide in the open tube. Hence the one test frequently confirms the other. Moistened litmus paper may be used in the mouth of the tubes to test any vapours given off, the blue colour turning red with acids.

Open tubes may often be cleaned out with a pipe-cleaner or by simple heating; closed tubes are seldom worth cleaning.

Precautions.—The upper part of a tube, though dried, must not be too hot to receive a sublimate.

Sublimates must be spread over a fair area, but will sometimes overlap on one another. Thus an arsenic mirror and the orange sulphide often produce at their junction an effect suggestive of antimonous sulphide.

SUBLIMATES IN THE TUBES.

CLOSED TUBE.	OPEN TUBE.	INDICATION.
Colourless drops.	... ...	*Water* (the tube must be well dried first).
Bright **Metallic "Mirror."**	**White**, showing minute sparkling crystals where thin. Garlic odour.	*Arsenic.*
Metallic Globules; seen to be liquid when touched with a rod.	As in closed tube.	*Mercury.*
Black; red streak when end of tube is cut off and sublimate is scraped out.	As in closed tube; some SO_2.	*Mercuric Sulphide.*
Dark-red to **Black.**	As in closed tube. Odour of "decaying horse-radish."	*Selenium* (rare).
Dark-red to **Black** (Black when hot).	**Dense White** (antimony oxides); some yellow sulphur and SO_2.	*Antimonous Sulphide.*
Orange (Dark red when hot). See precautions, p. 51.	As in closed tube, but breaking up into white crystalline oxide.	*Arsenous Sulphide.*
Yellow (sometimes almost white; orange-red only when hot).	As in closed tube, but soon converted into SO_2.	*Sulphur.*
	Dense White, often in part crystalline (oxides).	*Antimony.*
	Dense White, deposited on lower side of tube. (Lead sulphate.)	*Lead Sulphide.*
	White to **Yellow**, brown when hot. (Bismuthous oxide).	*Bismuth.*
	White, thin and crystalline. (Molybdenum trioxide.)	*Molybdenum.*

Certain special reactions in the tubes will be dealt with under the head of the substances of which they are characteristic.

H. Reactions on Charcoal.

(i.) ENCRUSTATIONS.

A small hole is cut with a knife-point in the charcoal, and a little powder of the assay is laid within it. Should it decrepitate or fly about, it should be moistened with a drop of water. It is then heated in O. F., the remainder of the flame being directed along the charcoal or the blackened surface of the support (see p. 38).

The substance may at once deflagrate, indicating the presence of a nitrate; or it may fuse more or less readily; it may colour the flame as in previous operations; or it may glow strongly, indicating lime, magnesia, strontia, zinc, or zirconia.

After heating for some time, a sublimate or "encrustation" will frequently form on the cooler part of the charcoal, or close under the fringe of the flame, according to the volatility of the product. Such encrustations are mostly due to oxides, and themselves disappear or shift on being heated in the flame, sometimes imparting a colour to it. In some cases they are developed while the assay itself is being treated in R. F. A thin white encrustation often appears blue when spread out over the black support, and thin yellow ones appear white upon the outer border.

If the encrustation is white, it should be allowed to cool and then be moistened with nitrate of cobalt solution dropped on it from a rod or pipette. Reheat strongly, counting about 200, and set aside to cool. In several cases characteristic colours result from the action of the cobalt. No transient colour need be regarded, as the strong heating mentioned is essential. The nitrate of cobalt solution dries first to a pink, then breaks up and turns black; but these colours speedily pass off and will cause no confusion. The charcoal into which any of the solution has sunk must be cut out, lest future encrustations should become coloured. It is also necessary to observe whether the ash of the charcoal alone gives any reaction with the nitrate.

As a refinement on ordinary methods, Dr. Haanel * employed plaster of Paris plates in place of charcoal, and hydriodic acid as a reagent, the encrustations observed being then due to iodides.

* *Trans. R. Soc. Canada*, vol. i. (1883), sect. 3, p. 65.

The plaster is made into a thin paste with water, and is spread out with a knife on a large glass plate to an even thickness of $\frac{1}{8}$ inch. Grooves are cut across the plaster, so that it can easily be broken, when set, into plates measuring 4 × $1\frac{3}{4}$ inches. The smooth surface produced next the glass is used for the encrustation, and a small hole is cut in it near one end for the assay, which is mixed with hydriodic acid. Messrs. Wheeler and Luedeking * use a mixture of 40 per cent. iodine and 60 per cent. sulphur added in excess to the assay, which is much simpler, and which gives equally striking and brilliant encrustations of metallic iodides on plaster of Paris.

Dr. Goldschmidt † uses mica or glass plates, resting on the charcoal, to receive encrustations. To prevent cracking, the latter are heated before use. The sublimate can thus be removed, and tested conveniently in the wet way.

A beautiful example of the oxidation of a metal before the blowpipe occurs in the cupellation of lead containing silver. The metallic bead is obtained from the ore by fusion with sodium carbonate on charcoal, and is removed and cleaned. A cupel of bone-ash is then made, about 2 cm. in diameter, being shaped in a hollow cut in charcoal, or struck in a mould, such as those provided in Letcher's blowpipe-cabinets. The cupel should be gently dried, and supported in a hollow of the charcoal. The metallic bead is placed on it in a little hollow near one side, and is treated in O.F. The lead oxidises, forming exquisite iridescent films on the bead itself, and red stains, which rapidly grow richer, on the bone-ash beyond. The cupel finally absorbs all the lead as oxide, and similarly any copper present; and silver, if present, remains behind as a gleaming and non-iridescent bead. This process requires some experience and repetition; the detailed account in Plattner's work (English edition of 1875, p. 369) shows to what perfection it may be carried.

* *Trans. St. Louis Acad. Sci.*, vol. iv. (1886), p. 676.
† Quoted in Keilhack, *Praktische Geologie*, p. 498.

ENCRUSTATIONS FORMED WITH THE OXIDISING FLAME.

COLOUR.	INDICATION.	WITH COBALT NITRATE.
White, yellow when hot.	*Molybdenum* (Turns a fine blue on the least touch of R. F.)	
	Tin (not volatile).	**Blue-green.**
	Zinc (not volatile).	**Yellow-green.**
White.	*Arsenic* (Very volatile and far from assay. Garlic odour.)	
	Antimony (denser).	**Dull Green.**
	Lead Chloride (thin).	
	Lead Sulphate. In these two last the yellow due to lead oxide appears within, and they burn blue when the flame is turned on to them.	
Yellow-brown.	*Cadmium.*	
Pink-brown, feeble. (Pale crimson on surface of antimony oxide, or when lead is present) (p. 63).	*Silver.*	
Yellow, passing into white. Orange when hot.	*Bismuth.* (A fine red results if equal parts of potassium iodide and sulphur are added to the assay.)	
	Lead (burns blue). Both the lead and bismuth encrustations have a white fringe, and become more intense in colour if this is driven back and concentrated upon them.	
Orange-yellow, very volatile.	*Arsenous Sulphide.*	
Red.	*Antimonous Sulphide.*	

(ii.) TREATMENT OF RESIDUAL ASSAY WITH NITRATE OF COBALT.

If the *residue of the assay* after oxidising is white or greyish, cobalt nitrate should be dropped upon it, and it should be strongly heated in O. F., as in the case of encrustations. This test is of especial service where no conclusive reaction has been hitherto obtained. On completely cooling, the colour may or may not have changed. The assay must be examined with a lens to ascertain whether fusion has taken place, since a blue colour after fusion has no determinative value. Similar reactions can be conveniently obtained by powdering the mineral, mixing with a drop of the solution, and taking up on a loop of platinum wire for treatment in the O. F.

The colours useful in determination are :—

COLOUR.	INDICATION.
Pale Pink or **Brown-pink.**	*Magnesia* (glows during ignition).
Green.	*Titanic oxide.*
Pale Blue.	*Alumina* (Blue after fusion is generally due to *Silica*).

(iii.) REDUCTION TO METAL IN THE REDUCING FLAME

Many ores can be reduced to metal in R. F. on charcoal, their volatile constituents going off as gas or becoming deposited as oxides on the charcoal. Other more refractory substances become reduced by being powdered with about three times their bulk of sodium carbonate; the mixture is then treated in R. F. on charcoal until all effervescence in the sodium carbonate has ceased, when often metallic globules will have separated out and have become distinctly visible in the flux. In many cases, however, the soda-slag must be cut out with a little of the charcoal under it and pounded out in water in an agate mortar; wash lightly with water, pressing firmly on the heavier residue with the pestle; metallic beads will often be found streaked out on the pestle, or in the mortar when the lighter admixture has been washed away.

The metallic beads obtained must, as a rule, be subjected to further tests. They should be treated by themselves on charcoal, to observe their purity and to see if they form an encrustation of any characteristic oxide; their malleability and sectility

should be examined; and they should be rubbed over a surface of white paper, under pressure from the clean base of the agate mortar, to determine whether or no they leave a streak such as is given by lead. Some bodies yield mere fused globular residues, which are brittle and can be referred to none of the undermentioned metals. Such residues can often be further decomposed; but alloys may be formed that are difficult to determine.

The bead or powdered residue from treatment in R. F. should always be tested with the magnet, and any matter that is attracted should be examined in a borax bead. Iron, cobalt, and nickel can be thus extracted and distinguished.

Precautions.—Search for possible small beads in the residue from fusion with sodium carbonate, as above described.

Rub beads in the mortar to clean off any oxide that may have formed during cooling, concealing their true metallic colour.

Nature of Metallic Bead.	Its Reactions.	Indication.
White, hard, malleable.	Does not mark paper. Placed on the margin of a film of antimony oxide formed on charcoal, and gently fused, will yield, with a little care, a pink encrustation over the white oxide.	*Silver.*
White, malleable, difficult to obtain without sodium carbonate.	Does not mark paper. Gives white encrustation and oxidises to a white powder, blue-green with cobalt nitrate.	*Tin.*
White, easily malleable.	Marks paper. Yellow encrustation; blue flame.	*Lead.*
White, cracks at edges when pressed; brittle.	Does not mark paper. Yellow encrustation.	*Bismuth.*
Copper-red, hard, malleable (often coated with black oxide).	No encrustation; green flame.	*Copper.*

NOTE.—*Arsenic*, *antimony*, and *zinc* are volatilised on reduction, and are recognised by encrustations and not as beads. *Mercury* and *arsenic* should be obtained by heating their compounds with sodium carbonate in a closed tube. *Iron*, *cobalt*, and *nickel* yield black magnetic residues, which should be tested in borax on platinum wire.

Certain reactions in which the use of sodium carbonate plays an important part will be described under the head of the substances of which they are characteristic. The **test for sulphur** alone need be mentioned here. Because a substance is a sulphate or even a sulphide, it by no means follows that evidence of sulphur will be given either in the closed or open tube. The decisive determination is made as follows :—Fuse thoroughly some of the powdered mineral with about three times its bulk of sodium carbonate in R. F., until effervescence ceases. Cut out the slaggy residue and the patch of charcoal below it, and crush on the surface of a clean silver coin with a drop of water. Allow it to lie for about ten seconds and wipe it off lightly. If sulphur has been present in any form, sodium sulphide will have resulted, which decomposes on the coin, leaving a brown or black stain of silver sulphide. This test is delicate and unfailing, and can be performed as a natural sequel to any good reduction with sodium carbonate, a portion of the slaggy mass being reserved for this purpose.

Precautions.—The reduction must be very thorough.

The charcoal below must be cut out, owing to its absorption of the sodium sulphide formed.

The sodium carbonate must itself be tested for sulphur; common gas also gives a slight reaction ; but the stains thus produced are ordinarily quite slight compared with those yielded by minerals, especially if the mass is not allowed to rest long upon the silver coin.

CHAPTER VI.

SIMPLE AND CHARACTERISTIC REACTIONS OF THE CONSTITUENTS OF COMMON MINERALS.

ABBREVIATIONS used:—*Flame* = Flame-colouration. *Fus.* = Fusibility. *Bor.* = Borax bead. *Micr.* = Microcosmic salt bead. *Cl. tube* = Closed tube. *O. tube* = Open tube. *Ch.* = On charcoal. Soda = Sodium carbonate. H Cl = Hydrochloric acid. *Add.* = Additional reactions. The most useful and characteristic reactions are preceded by an asterisk. Details must be looked for on pp. 45 to 60.

Aluminium.—* *Ch.*—Alumina becomes blue with cobalt nitrate; if the surface is fused, the reaction is indecisive. Dissolve the

soda-residue in dilute H Cl, evaporate to dryness, redissolve in H Cl and water, filter off any silica, and neutralise with ammonia; alumina is precipitated, together with any iron that may be present. The precipitate, if white or nearly so, can be tested with cobalt nitrate, the resulting fine blue colour distinguishing it from glucina, which is similarly precipitated. Glucina, however, is of rare occurrence.

Antimony.—*Flame*—Blue-green or green-blue. *Cl. tube*—Some white oxides; dark red when sulphur is present. * *O. tube*—Dense white oxides, sometimes crystalline. * *Ch.*—Ditto. Dull green with cobalt nitrate. (See note on p. 64.)

Arsenic.—*Flame*—Blue, smoky through formation of oxide. * *Cl. tube*—Metallic mirror, particularly with soda. Some white crystalline oxide. With sulphur, orange-yellow. * *O. tube*—White crystalline oxide, garlic odour. *Ch.*—Ditto, far from assay.

Barium.—* *Flame*—Yellow-green.

Bismuth.—*O. tube*—Oxide sometimes formed. * *Ch.*—Yellow encrustation, bordered with white. With sulphur and potassium iodide yields red encrustation of bismuthous iodide. Bead somewhat brittle, not marking paper.

Boron.—* *Flame*—Green. Use sulphuric acid or even fluor-spar and bisulphate of potash.

Cadmium.—* *Ch.*—Brown oxide. Use soda.

Calcium.—* *Flame*—Red to yellow-red. Glows strongly. *Add.*—Dissolve assay in HCl, and dilute greatly. Add sulphuric acid; no precipitate occurs (see "Strontium").

Carbon Dioxide.—* Carbonates effervesce in HCl, some when cold, all when heated. A little water must be added. Sulphides that behave similarly are recognised by their physical characters and by the smell of the escaping gas, sulphuretted hydrogen. Small quantities of carbonate of lime, &c., present only as impurities in the assay, often give considerable effervescence.

Chlorine.—* *Micr.*—Make a very dark bead with copper and add a little of the assay. If chlorine is present in fair quantity, a fine blue flame surrounds the bead when it is again introduced into the flame. (See p. 43.) Bromine gives a similar reaction, but is far less often met with.

Chromium.—* *Bor.*—Fine green in both flames. *Micr.*—Ditto.

Cobalt.—* *Bor.*—Blue in both flames. *Micr.*—Violet to blue beads. The borax beads are green when iron is present, especially when hot. *Ch.*—Residue from R.F. magnetic.

Copper.—* *Flame*—Bright green. Blue near assay with H Cl. *Bor.*—O.F., green to blue; R.F., opaque red. *Micr.*—Ditto. *Ch.*—Metallic bead of copper; use soda in most cases.

Fluorine.—* *Cl. tube*—If decomposable, heat the powdered assay strongly with a drop or two of sulphuric acid; hold a clean glass microscopic slip, or the base of a watch-glass, close down on the end of the tube. In two or three minutes remove and wash. When dried, a dulled circular area will be seen, due to etching by the hydrofluoric acid vapours. If sand or quartz fragments are added with the sulphuric acid, silicic fluoride is formed. Insert a glass rod moistened with water down the tube; the water decomposes the vapour, and white silicic hydrate is deposited on the rod.

Add.—If the mineral is not decomposed by H_2SO_4, fuse microcosmic salt on charcoal until ebullition ceases, mix the product with the powdered assay, and fuse on a glass slip over a lamp-flame. On washing off the mixture and drying, the surface will be seen to be etched, a dulled area having been formed under the fused mass.

Iron.—* *Bor.*—O. F., yellow. R. F., bottle-green. * *Micr.*—Reddish in both beads; darker when titanium or tungsten is present (see under these). *Cl. tube*—Residue sometimes magnetic. * *Ch.*—Residue from R. F. magnetic.

Lead.—* *Flame*—Blue. *O. tube*—When sulphur is present, forms, on some heating, a dense white deposit of lead sulphate. **Ch.*—Yellow to orange oxide, fringed with white; turns strong yellow when potassium iodide and sulphur are added to assay. White chloride or sulphate when chlorine or sulphur is present. Metallic lead in R. F. The bead oxidises and turns orange in O. F.

Lithium.—* *Flame* – Crimson. A rare constituent.

Magnesium.—* *Ch.*—Magnesia becomes dull pink with cobalt nitrate. Heat strongly. Few compounds, however, show this reaction, and wet tests must be used.

Manganese.—* *Bor.*—O. F., red violet. R. F., colourless. *Micr.*—Ditto. *Add.*—* Moisten a loop of platinum wire, and dip it into sodium carbonate; fuse to a bead and add the powdered assay; heat in O. F.; manganese, even in very small quantity, gives an opaque green bead.

Mercury.—* *Cl. tube*—Metallic sublimate, especially with soda. The sulphide, without soda, gives a black sublimate which has a red streak.

Molybdenum.—*Flame*—Yellow-green. * *Bor.*—O. F., colourless. R. F., brown. *Micr.*—Green in both flames. *O. tube*—Sometimes thin white oxide. * *Ch.*—White oxide, which becomes *blue on being touched with R. F. The soda-residue, treated as described under "Titanium," gives a

greenish solution which passes into brown; sometimes blue. (See "Tungsten.")

Nickel.—* *Bor.*—O. F., brown. R. F., greyish. * *Micr.*—O. F., yellow. R. F., slowly colourless with tin. These reactions may be obscured by cobalt. See account of chloanthite on p. 69. *Ch.*—Residue from R. F. magnetic.

Phosphorus.—* *Flame*—Feebly but distinctly green; use sulphuric acid. *Cl. tube*—Add 4 mm. or so of magnesium tape and fuse. In some cases the mineral must be first fused with soda on charcoal, and the powdered slag used in the tube. The addition of water, after the tube has cooled, causes the evolution of phosphoretted hydrogen, known by its smell, which is compared to that of decaying fish. *Ch.*—With cobalt nitrate fusible phosphates become blue. *Add.*—* Nitric acid solution of ammonium molybdate, added to a solution of a phosphate, or in many cases to its powder, produces a crystalline yellow precipitate. This must be proved to be crystalline with a lens or microscope.

Potassium.—**Flame*—Violet. Often requires blue glass. For intensification of this reaction, see pp. 83, 85. * *Add.*—Fuse the assay with soda on platinum, if not otherwise soluble, and dissolve in H Cl. Add solution of platinic chloride, and evaporate almost to dryness; add a little water, or preferably alcohol; if potassium is present, a crystalline yellow precipitate of potassium platinic chloride will be seen to have formed. This precipitate is not easily dissolved in water, and is insoluble in alcohol. Ammonium compounds give a similar reaction.

Silicon.—* *Micr.*—Silica is insoluble, a skeleton thus remaining in the bead. The fragment used must be small (see p. 52). * *Ch.*—The soda-residue should be dissolved in dilute H Cl, evaporated to dryness at a temperature only a little above 100°, and again treated with H Cl and water. Any silica present will separate as a light precipitate, which must not feel gritty under the glass rod used in stirring. If gritty, the fusion with soda has not been carried on long enough to completely decompose the assay.

With cobalt nitrate fusible silicates give a rich blue glass. *Add.*—Some silicates decompose on boiling with H Cl, the silica being left as a powder or a jelly of silicic hydrate (see p. 33). If previously fused with soda, a jelly always forms.

Silver.—*Bor.* and *Micr.*—White and turbid beads, particularly in O. F. *Ch.*—Dull pink brown feeble encrustation, pale crimson or violet if formed over a film of oxide of antimony, or where lead is present, the colour greatly improving on cooling. An

ore of antimony may be added to the assay, to produce this reaction. * Silver bead in R.F., which does not mark paper like lead, or turn white like tin in O.F. Where copper is present, or in any compound ore of silver, it is well to use a mixed flux of borax and soda, the borax taking up the other constituents. (In presence of lead, see p. 56.)

Sodium.—* *Flame*—Strong yellow.

Strontium.—* *Flame*—Crimson to yellowish-red. *Add.*—Dissolve assay in H Cl, and dilute greatly. Add sulphuric acid; a white precipitate occurs, sometimes after a little standing (see "Calcium").

Sulphur.—*Flame*—Native sulphur gives a blue flame, but this is not seen in the heating of sulphides and sulphates. *Cl. tube*—Yellow sublimate from many minerals, the colour most noticeable when hot. *O. tube*—Sulphurous anhydride is often evolved. * *Ch.*—Blackens silver coin after fusion in R.F. with soda and addition of water to the slag (see p. 60). *Add.*—Treated with H Cl, many sulphides give off sulphuretted hydrogen, known by its smell.

Sulphides may in all ordinary cases be distinguished from sulphates by their physical characters.†

Tin.—*Ch.*—White encrustation, somewhat weak at first; * blue-green with cobalt nitrate. * Metallic beads, white and malleable; best obtained by powdering the assay with charcoal and soda, then fusing, and pounding out of the residue in water in a mortar. The bead turns white in O.F.

Titanium.—*Bor.*—O. F., colourless. R. F., yellow to brown. * *Micr.*—O. F., colourless. R. F., violet. Dark red-brown when iron is present. * *Ch.*—The soda residue is boiled in H Cl, with tin-foil about one centimetre square, to ensure reduction, and to avoid colouration of the liquid by formation of ferric chloride, should iron be present. On cooling, and often after some standing, the solution becomes violet through formation of titanium trichloride ($TiCl_3$). (See "Tungsten" below.)

Tungsten.—*Bor.*—O. F., colourless. R. F., palish yellow-brown. *Micr.*—O. F., colourless. R. F., blue. Crimson-brown or red if iron is present. * *Ch.*—The soda-residue, treated as above described under "Titanium," gives a Prussian-blue solution, sometimes turning brown later. The charcoal used in the fusion must not contain any cobalt nitrate from previous operations, since this will produce a similar blue in the acid. Some salts of molybdenum are said to behave similarly.

† For a rapid method for the determination of sulphides, arsenides, and antimonides, see Burghardt, *Mineral Mag.*, vol. ix. (1891), p. 227.

Uranium.—* *Bor.*—O.F., yellow. R. F., bottle-green. * *Micr.* —Green beads. Distinguished thus from iron.

Zinc.—* *Ch.*—White encrustation, bright green with cobalt nitrate; heat assay in R. F. No metallic bead.

Zirconium.—*Flame*—Zirconia glows very strongly. *Ch.*—With cobalt nitrate zirconia becomes dull violet, a reaction uncertain and difficult to obtain in the case of zircon, the only common compound of zirconia. (See notes on Zircon on p. 77.)

CHAPTER VII.

BLOWPIPE-TESTS USEFUL IN THE DETERMINATION OF COMMON MINERALS.

THE selection of minerals here made includes some that are of far rarer occurrence than others, but which yet are the more common representatives of certain chemical constituents of the earth's crust. It also excludes a number of important minerals, particularly silicates, which must be recognised by physical characters or more complete chemical analysis. The group, for example, of the felspars thus obtains little prominence; but the later section devoted to Szabó's flame-reactions does them, it is hoped, some measure of justice. The worker is presumed to have before him some handy text-book of mineralogy, and questions of colour, hardness, &c., are thus omitted from these notes, except where especially important for distinction. Should the mineral under examination not correspond with any in the following series, reference to the text-book under the head of those that agree with it most closely will generally complete its determination.

An alphabetical order has been adopted; but an index at the end of the list serves to connect the ores of the same metal one with another. The abbreviations used are the same as those in the preceding section. The chemical composition is shown after each name.

1*a*. **Alunite** (see notes on **Websterite**).

1. **Anglesite.** $Pb\,S\,O_4$. *O. tube*—Fuses, and on prolonged heating forms a slight white sublimate. *Ch.*—Lead encrustation. Fuses and reduces easily to metal. With soda, sulphur reaction. *Add.*—Despite its appearance, the specific gravity (= 6·2) suggests the presence of a heavy metal.

2. **Anhydrite.** $Ca\,S\,O_4$. *Flame*—Calcium, with H Cl. *Fus.*—About 2·5. *Cl. tube*—No water. *Ch.*—With soda, sulphur reaction. *Add.*—Hardness = 3 or more; that of gypsum = 2. Soluble in H Cl.

3. **Anorthite.** $Ca\,Al_2\,Si_2\,O_8$. *Flame*—Calcium, on decomposition with H Cl. *Fus.*—Nearly as high as orthoclase. *Micr.*—Silica. *Add.*—Best treated by Szabó's method. Decomposed by H Cl. Specific gravity = about 2·75.

4. **Antimonite.** $Sb_2\,S_3$. *Flame*—Smoky green. *Fus.*—1. *Cl.*

tube—Red sublimate of antimonous sulphide, darkening to black at base; white oxides, and sometimes sulphur, above. *O. tube*—Similar; dense white oxides. *Ch.*—Similar products; in the end completely volatilised. With soda, sulphur reaction.

5. **Apatite.** $3\,Ca_3\,P_2\,O_8 + Ca\,(Cl, F)_2$. *Flame*—With H Cl, calcium flame; with H_2SO_4, phosphorus. *Fus.*—Near 5. *Cl. tube*—With magnesium, phosphorus reaction. *Add.*—Soluble in strong H Cl. A drop of sulphuric acid added to the solution precipitates microscopic crystals of gypsum. Treated with nitric acid and ammonium molybdate solution, gives strong yellow precipitate. Small fragments may be thus dealt with on a glass slip.

6. **Apophyllite.** Very near $(H, K)_2\,Ca\,Si_2\,O_6 + H_2\,O$, with some Fl. *Flame*—With blue glass, good potassium. *Fus.*—Easy, with intumescence. *Micr.*—Silica. *Cl. tube.*—Water. *Add.*—With H Cl gives gelatinous silica in lumps.

7. **Aragonite.** $Ca\,C\,O_3$ (Rhombic form).—*Flame*—With H Cl, strong calcium. *Fus.*—Infusible. *Add.*—Effervesces freely in cold H Cl. The solution is greatly diluted, gives no precipitate on addition of sulphuric acid, even after long standing. Distinguished thus from strontianite. Distinguished from calcite by its specific gravity (= 2·93) and slightly superior hardness. For Meigen's and Lemberg's important tests, see p. 36.

8. **Argentite.** $Ag_2\,S$. *Fus.*—Easy. *Bor.* and *Micr.*—Silver reactions. *Ch.*—Silver bead. With soda, sulphur reactions. *Add.*—Sectile and malleable. Distinguished from stephanite by absence of antimony.

9. **Atacamite.** $Cu\,Cl_2 + 3\,H_2\,Cu\,O_2$. *Flame*—Burns luminously, and gives a blue flame near the assay (copper chloride) and copper green beyond. *Bor.* and *Micr.*—Copper reactions. *Cl. tube*—Water. Forms yellow-brown and greenish deposits at lower end of tube. *Ch.*—Similar deposits on the charcoal. Copper bead.

10. **Augite.** (Ca, Mg, Fe) $Si\,O_3$ with some $Al_2\,O_3$ and Fe_2O_3.* *Fus.*—About 3·5. *Micr.*—Silica. *Add.*—Can be just scratched with a knife. Prism-angle of 87° distinguishes the pyroxenes from the amphiboles.

11. **Azurite.** $2\,Cu\,C\,O_3 + H_2\,Cu\,O_2$. *Flame*—With H Cl, copper colours. *Fus.*—2. *Bor.* and *Micr.*—Copper reactions. *Cl. tube*—Blackens; water given off. *Ch.*—Copper bead. *Add.*—Effervesces freely in hot H Cl. Distinguished from malachite by blue colour; from chalcanthite by absence of sulphur and insolubility in water.

12. **Barytes.** $Ba\,S\,O_4$. *Flame*—Barium green. *Fus.*—About 3; commonly decrepitates. *Ch.*—With soda, sulphur reaction.

* See Hintze, *Mineralogie*, Bd. ii., p. 958.

Add.—Specific gravity = 4·5, a character noticeable even in small specimens.

13. **Bismuth.** Bi. *Fus.*—Very easy. *O. tube*—Fuses and forms white to pale yellow sublimate; if potassium iodide and sulphur are fused with it, a vermilion sublimate results. *Ch.*—Bismuth encrustation, which becomes a strong red when potassium iodide and sulphur are added to the assay. These materials should be powdered up with the bismuth. Fuses to a brittle but slightly malleable bead, which does not mark paper.

Bismuthine ($Bi_2 S_3$) gives similar reactions, but with evidences of sulphur.

13*a*. **Blende** (see **Zinc Blende**).

14. **Bornite.** $Cu_3 Fe S_3$. *Flame*—Copper. *Fus.*—Easy. *Bor.* and *Micr.*—Copper reactions. *Ch.*—Fuses to a magnetic globule. With soda, copper beads in a black magnetic residue (iron). Sulphur reaction. *Add.*—Distinguished by purple-red tarnish from copper pyrites; yellowish when freshly fractured.

15. **Brucite.** $H_2 Mg O_2$. *Fus.*—Infusible; becomes opaque. *Cl. tube*—Water. *Ch.*—With cobalt nitrate gives a faint magnesium reaction. Compare with talc and gypsum (see also p. 36).

16. **Calamine** (**Smithsonite** of Beudant). $Zn C O_3$. *Ch.*—Zinc encrustation, which, with the residue, becomes a fine green with cobalt nitrate. *Add.*—Effervesces in $H Cl$. Distinguished from hemimorphite (calamine of Brongniart) by not yielding gelatinous silica.

17. **Calcite.** $Ca C O_3$ (rhombohedral form). Like **Aragonite** (but see p. 36). *Add.*—Specific gravity = 2·72. Perfect rhombohedral cleavage, even in small fragments.

18. **Cassiterite.** $Sn O_2$. *Micr.*—Often some silica. *Ch.*—Tin encrustation, blue-green with cobalt nitrate; near the assay, and very characteristic if examined when cold. Powder with one part of charcoal and two parts of soda, to obtain good metallic beads. The metallic bead, treated alone on charcoal in O. F., oxidises and turns white, unlike lead or silver. *Add.*—Specific gravity = about 6·8, an important character when examining the dull brown pebbles of **Stream Tin.**

19. **Celestine.** $Sr S O_4$. *Flame*—Strontium. *Ch.*—With soda, sulphur reaction. *Add.*—Distinguished from gypsum, should the flame be doubtful, by hardness = 3 – 3·5 and specific gravity = 3·95; also absence of water, and insolubility in $H Cl$. The latter character distinguishes it from anhydrite.

20. **Cerussite.** $Pb C O_3$. *Flame*—Lead. *Fus.*—Very easy. *Cl. tube*—Becomes yellow on cooling (lead oxide). *Ch.*—Lead encrustation; rapidly reduced to metal. *Add.*—Effervesces in

hot H Cl. Specific gravity = 6·4 when crystallised, suggesting, in spite of its appearance, the presence of a heavy metal.

20*a*. **Chalcopyrite** (see **Copper Pyrites**).

21. **Chalybite.** $Fe\,C\,O_3$. *Fus.*—Near 5; blackens. *Bor.* and *Micr.*—Iron reactions. *Cl. tube.*—Blackens; magnetic residue. *Ch.*—Ditto. *Add.*—Effervesces in hot H Cl.

22. **Chloanthite.** $(Ni, Co, Fe)\,As_2$. *Fus.*—Easy. *Bor.*—Cobalt reaction. If much iron is present, the bead will be green when hot. To obtain evidence of the nickel, prepare a large well-coloured borax bead and transfer it to charcoal; oxidise for some time; separate the blue glass from the metallic residue by breaking the bead, wrapped in paper, on the anvil; fuse the residue again with more borax on the charcoal, and repeat the operation until the bead becomes brown (nickel) or colourless (no nickel present). To confirm this result, treat the residue now with microcosmic salt, which will show the characteristic yellow due to nickel in O. F. If copper is also present, the microcosmic salt bead will be green, and will become red in R. F. on addition of tin.

Where the quantity of nickel is small, a gold button weighing about 75 milligrammes should be fused with the borax bead on charcoal. This withdraws the nickel and any copper, and, after fusion with fresh borax to remove all cobalt, gives with microcosmic salt the nickel or nickel and copper reaction.

The colours of beads thus treated on charcoal can always be examined by picking up some of the hot material on platinum wire. *Cl. tube*—Arsenic sublimates. *Ch.*—Abundant arsenic encrustation.

23. **Chromite.** $(Fe, Cr)(Fe_2, Cr_2)O_4$, often with $Mg\,O$ and $Al_2\,O_3$. *Fus.*—Practically infusible; becomes magnetic in R. F. *Bor.* and *Micr.*—Fine chromium reactions; mingled with those of iron when hot. *Ch.*—In R. F. somewhat feebly magnetic residue.

24. **Chrysocolla.** Probably $H_2Cu\,Si\,O_4 + H_2O$. *Flame*—Copper. *Fus.*—Infusible. *Bor.* and *Micr.*—Copper reactions. In latter, cloudy silica. *Cl. tube*—Water; becomes black. *Ch.*—With soda, metallic copper. *Add.*—With H Cl, separation of powdery silica. Commonly some carbonate present.

25. **Cinnabar.** Hg S. *Cl. tube*—Black sublimate, which has a red streak. With soda added, yields globules of mercury. *Ch.*—Volatilises. With soda, sulphur reaction. With potassium iodide and sulphur, faint yellow encrustation. *Add.*—Red streak.

26. **Cobaltine.** $Co\,As_2 + Co\,S_2$ (= Co As S). *Bor.* and *Micr.*—Cobalt reactions. *Cl. tube*—Fuses. Arsenous sulphide, sulphur,

white oxide, and sometimes some metallic arsenic. *O. tube*—White oxide and some sulphide. *Ch.*—Arsenic encrustation.

27. **Copper Pyrites (Chalcopyrite).** $Cu\,Fe\,S_2$. *Flame*—Copper colours with $H\,Cl$. *Fus.*—Easy. *Bor.* and *Micr.*—Copper reactions; green in O. F. when hot, owing to presence of iron. *Cl. tube*—Some sulphur. *Ch.*—Fuses to a magnetic globule. Roast in O. F., and then reduce; a copper bead separates in the mass. Soda only obscures the reaction. *Add.*—Hardness = 3·5; easily distinguished thus from iron pyrites, which cannot be scratched by the knife.

27*a*. **Copper Glance** (see **Redruthite**).

28. **Corundum.** $Al_2\,O_3$. *Fus.*—Infusible. *Micr.*—Very slowly soluble; often some silica. *Ch.*—With cobalt nitrate the residue becomes pale blue (alumina). *Add.*—Hardness = 9; specific gravity = 4. These characters are both important when dealing with rough forms, such as the pebbles found in streams. The parting-planes are generally traceable even in these.

29. **Cryolite.** $6\,Na\,F + Al_2\,F_6$ ($= Na_6\,Al_2\,F_{12}$). *Flame*—Sodium. *Fus.*—Very easy. *Cl. tube*—Fluorine reaction with sulphuric acid. *Ch.*—After thorough heating, the residue gives alumina reaction with cobalt nitrate. *Add.*—Fused with microcosmic salt on a glass slip, leaves a dulled and etched area when the slip has been washed and dried. Distinguished from fluor-spar by its lower hardness (= 2·5) and its easy fusibility.

30. **Cuprite.** $Cu_2\,O$. *Flame*—Copper colours with $H\,Cl$. *Fus.*—Easy. *Bor.* and *Micr.*—Copper reactions. *O. tube*—Blackens ($Cu\,O$). *Ch.*—Copper bead in R. F. easily obtained. *Add.*—Soluble in $H\,Cl$. Streak red.

31. **Dolomite.** $Ca\,Mg\,C_2\,O_6$. *Flame*—With $H\,Cl$, calcium. *Fus.*—Infusible. *Add.*—In cold dilute $H\,Cl$ (50 per cent. water) effervesces very slightly, but freely when heated. Compare with calcite by putting a fragment of each in the same tube. For Lemberg's test, see p. 36.

To the $H\,Cl$ solution add slight excess of ammonia, and then solution of hydric disodic phosphate (1 part of the salt to 10 of water). Allow to stand for some time. A minutely crystalline precipitate of ammonic magnesic phosphate will be formed.

The specific gravity of dolomite is about 2·85, calcite being 2·72; the hardness is between 3·5 and 4.

32. **Epidote.** $H\,Ca_2\,(Al, Fe)_3\,Si_3\,O_{13}$. *Fus.*—Slightly more fusible than actinolite. Intumesces somewhat. *Micr.*—Silica. *Add.*—Hardness = 6·5, that of the amphiboles being 5·5.

33. **Epsomite (Epsom Salt).** $Mg\,S\,O_4 + 7\,H_2O$. *Fus.*—Very easy, with intumescence. *Cl. tube*—Water. *Ch.*—With cobalt nitrate, magnesia reaction. With soda, sulphur reaction. *Add.*—Soluble in water. Bitter taste.

33*a*. **Erubescite** (see Bornite).

34. **Fluor-spar.** $Ca\,F_2$. *Flame*—Calcium, fairly good. *Fus.*—Decrepitates much, but finally fuses at 2·5 – 3 with ebullition. *Cl. tube*—Fluorine reactions well given. Sometimes phosphorescent. *Add.*—Fused with microcosmic salt on a glass slip, etches the glass beneath. Distinguished from calcite by its superior hardness and specific gravity.

35. **Franklinite.** $(Fe, Zn, Mn)\,(Fe_2, Mn_2)\,O_4$. *Fus.*—Infusible. *Bor.* and *Micr.* — Iron reactions. *Ch.* — Zinc encrustation, green with cobalt nitrate. *Add.*—Manganese reaction with soda bead. More or less magnetic even before reduction.

36. **Galena.** $Pb\,S$. *Flame*—Lead. *Fus.*—Very easy. *Cl. tube*—Thin white-yellow sulphur sublimate. *O. tube*—After strong heating, a distinct and characteristic heavy sublimate of lead sulphate forms as a white streak on the under side of the tube. *Ch.*—Lead encrustation fringed with lead sulphate. Metallic lead bead easily obtained. With soda, sulphur reaction. *Add.*—Colour and cubic cleavage characteristic, even in small fragments. For Argentiferous Galena, see p. 56.

37. **Garnet.** Common varieties represented by $(Ca, Fe, Mg, Mn)_3\,(Al_2, Fe_2, Cr_2)\,Si_3\,O_{12}$. *Fus.*—The common iron-alumina and lime-iron garnets fuse at 3. *Micr.*—Silica. *Add.*—The crystalline forms, rhombic dodecahedron, icositetrahedron, &c., are characteristic, and can be traced even in worn specimens. Hardness = about 7; specific gravity = about 3·5, but not safely distinguished thus from ruby (red corundum). The low fusibility of most varieties easily distinguishes red garnets from ruby, zircon, and spinel.

38. **Göthite.** $H_2\,Fe_2\,O_4$. *Fus.*—About 5. *Bor.* and *Micr.*—Iron reactions. *Cl. tube*—Water. *Ch.*—In R. F. magnetic residue. *Add.* — Soluble in $H\,Cl$ after some time. Streak yellow-brown. Crystallises, and has somewhat higher specific gravity than limonite (4·2 and 3·8 respectively, averages being taken).

39. **Graphite.** C. *Fus.*—Infusible. *Bor.*—In R. F. gives dusky bead full of black flecks, resembling that due to molybdenum. *Add.*—Soils the fingers. Does not give the yellow-green flame of molybdenite, which has specific gravity =

4·5, that of graphite being only 2. Graphite is also blacker in colour.

40. **Gypsum.** $Ca\,S\,O_4 + 2\,H_2\,O$. *Flame*—Calcium, with H Cl. *Fus.*—About 2·5. *Cl. tube*—Becomes white and opaque; much water. *Ch.*—With soda, sulphur reaction. *Add.*—Hardness = 2. Soluble in H Cl. See **Celestine.**

41. **Hæmatite.** $Fe_2\,O_3$. *Fus.*—Fusible on reduction in R. F. *Bor.* and *Micr.*—Iron reactions. *Cl. tube*—Generally a trace of water, but far less than limonite or göthite. *Ch.*—In R. F. magnetic residue. *Add.*—Slowly soluble in H Cl. Streak red (highly characteristic, even of the black **Specular Iron** variety).

42. **Hemimorphite (Electric Calamine).** $H_2\,Zn_2\,Si\,O_5$. *Fus.*—6. *Micr.*—Silica. *Cl. tube*—Water. *Ch.*—Zinc encrustation. *Add.*—Soluble in H Cl with formation of a stiff silica jelly. Commonly associated with some carbonate of zinc, which effervesces.

43. **Hornblende.** (Mg, Ca, Fe) $Si\,O_3$, with some $Al_2\,O_3$ and Fe_2O_3.* Like augite. Prism-angle, however, 124°. Frequently in elongated prisms and even finely fibrous, as in **asbestos.**

43*a*. **Horn Silver** (see **Kerargyrite**).

43*b*. **Ilmenite** (see **Titanic Iron Ore**).

44. **Iron.** Fe. *Fus.*—Infusible. *Bor.* and *Micr.*—Iron reactions. *Add.*—Magnetic. Soluble in H Cl, giving yellow solution. Placed in a drop of aqueous solution of cupric sulphate, becomes coated with metallic copper. Reduces the test solution of ammonium molybdate, producing a fine blue colour.

Rare except in meteorites: the cupric sulphate test has been applied to microscopic sections.

45. **Iron Pyrites (Pyrite).** $Fe\,S_2$. *Fus.*—About 2. *Bor.* and *Micr.*—Iron reactions. *Cl. tube*—Abundant sulphur. *Ch.*—Magnetic after reduction. *Add.*—Insoluble in H Cl. Crystallises commonly in cubes. Distinguished from pyrrhotine by more brassy colour, hardness (= 6·5), behaviour with H Cl, and particularly by not being magnetic before fusion. Marcasite is slightly paler in colour. See **Marcasite.**

46. **Kaolin.** $H_4\,Al_2\,Si_2\,O_9$. *Fus.*—Infusible. *Micr.*—Silica. *Cl. tube*—Water. *Ch.*—With cobalt nitrate, a fine alumina reaction.

47. **Kerargyrite (Horn Silver) Group.**† Ag (Cl, Br, I). **Chlorargyrite** (Ag Cl) is grey or colourless. *Micr.*—With copper, chlorine reaction. *Cl. tube*—Fused with potassium bisulphate,

* See Hintze, *Mineralogie*, Bd. ii., p. 1186.
† Prior and Spencer, *Min. Mag.*, vol. xiii. (1902), p. 175.

evolves H Cl. *Ch.*—Silver bead. **Bromargyrite** (Ag Br) is greenish-grey. *Cl. tube*—Treated as above, evolves bromine. The species containing iodine are yellowish.

48. **Kupfernickel (Nickeline).** Ni As. *Fus.*—Very easy. *Bor.* and *Micr.*—Nickel reactions. If complicated by cobalt, must be treated as described under chloanthite. *Cl. tube*—No arsenic mirror. *O. tube*—White oxide. *Ch.*—Arsenic encrustation. In R. F., magnetic globule. *Add.*—Insoluble in H Cl. Copper-red colour characteristic.

49. **Labradorite.** For composition, see p. 173. *Flame*—Calcium and sodium, the former often overpowered by the latter. *Fus.*—3·5. *Micr.*—Silica. *Add.*—Slowly decomposed by H Cl. Best treated by Szabó's method. Specific gravity = about 2·7.

50. **Limonite.** $H_6 Fe_4 O_9$. Like göthite; but specific gravity somewhat lower (= about 3·8). Not found crystallised.

51. **Magnesite.** $Mg C O_3$. *Fus.*—Infusible. *Ch.*—With cobalt nitrate, fair magnesia reaction. *Add.*—Effervesces fairly in hot H Cl. (See p. 36.)

52. **Magnetite.** $Fe_3 O_4$. *Fus.*—6. *Bor.* and *Micr.*—Iron reactions. *Add.*—Slowly soluble in H Cl. Magnetic before reduction, attracting its own powder. Many masses show polar magnetism of opposite kinds. Compare notes on **Titanic Iron Ore.**

53. **Malachite.** $Cu C O_3 + H_2 Cu O_2$. Like azurite. Green colour highly characteristic. Distinguished from chrysocolla by absence of silica and by less porcellanous aspect.

53*a*. **Manganite** (see notes on **Psilomelane**).

54. **Marcasite.** $Fe S_2$. Like pyrite, but white when cleaned with H Cl.* Readily decomposed on exposure to the atmosphere.

55. **Mispickel.** Fe As S ($= Fe As_2 + Fe S_2$). *Fus.*—2. *Bor.* and *Micr.*—Iron reactions. *Cl. tube*—Arsenous sulphide and excellent arsenic mirror. *O. tube*—White oxide. *Ch.*—Ditto. Magnetic residue in R. F. With soda, sulphur reaction. *Add.*—When containing cobalt, difficult to distinguish from smaltite, but contains far more iron, and is rhombic, not cubic, in crystallisation.

56. **Molybdenite.** $Mo S_2$. *Flame*—Molybdenum, resembling barium. *Fus.*—Infusible. *Bor.* and *Micr.*—Molybdenum reactions. *O. tube*—Faint white molybdenum trioxide. *Ch.*—White encrustation, at some distance, when an unusually large

* H. N. Stokes, *Bull. U.S. Geol. Survey*, No. 186 (1900).

assay is used; this encrustation at once turns a fine blue colour when touched with R. F. With soda, sulphur reaction. The product of the soda-fusion, boiled with tin in H Cl, colours the fluid greenish and finally brown. *Add.*—Bluer in tint than graphite; marks paper with a greenish streak.

57. **Natrolite.** $Na_2Al_2Si_3O_{10} + 2H_2O$. *Flame*—Strong sodium. *Fus.*—2. *Cl. tube*—Water. *Micr.*—Silica. *Add.*—With H Cl forms a strong silica-jelly. Hardness, like many zeolites, = 5·5, but often appears less, through fibrous structure.

58. **Nepheline (Elæolite).** Approximately (Na, K) Al Si O_4, but seems to contain slightly more silica. *Flame*—Sodium. *Fus.*—3·5. *Micr.*—Silica. *Add.*—With H Cl forms a strong silica-jelly.

58*a*. **Nickeline** or **Niccolite** (see **Kupfernickel**).

59. **Nitre.** K N O_3. *Flame*—Fine Potassium. *Fus.*—Very easy. *Cl. tube*—Fused with bisulphate of potash, gives off brown fumes, well seen on looking down tube. *Ch.*—Flares up directly it is touched with the flame, forming potassium carbonate. *Add.*—Soluble in water. Characteristic taste.

60. **Oligoclase.** For composition, see p. 173. *Flame*—Sodium. *Fus.*—3·5. *Micr.*—Silica. *Add.*—Specific gravity = about 2·63. Not decomposed by H Cl. Best treated by Szabó's method.

61. **Olivine.** $(Mg, Fe)_2 Si O_4$. *Fus.*—Infusible. *Micr.*—Silica. *Add.*—Most common varieties give a silica-jelly with H Cl. Transparent yellow-green appearance characteristic. H = 6 - 7.

62. **Orthoclase.** (K, Na) Al Si_3 O_8. *Flame*—Often much sodium (**Soda-Orthoclase**). To observe the strong potassium flame, fuse in a bead of sodium carbonate and examine through 5 mm. of blue glass (see also p. 85). *Fus.*—5. *Micr.*—Silica. *Add.*—Not decomposed by H Cl. Specific gravity = about 2·56.

63. **Pitchblende.** mU O_2 + nU O_3. *Fus.*—6. *Bor.* and *Micr.*—Uranium reactions. In *Micr.*, generally silica. *Add.*—Liable to give many reactions due to impurities of sulphur, copper, &c. The microcosmic salt beads are the most conclusive blowpipe-reaction.

64. **Proustite.** $Ag_3 As S_3$ (= 3 Ag_2 S . $As_2 S_3$). *Fus.*—1. *Bor.* and *Micr.*—Silver reactions. *Cl. tube*—Some arsenous sulphide. *O. tube*—White oxide. *Ch.*—Arsenic encrustation. With soda, silver bead and sulphur reaction. *Add.*—Streak scarlet-vermilion (*Miers*); see **Pyrargyrite.**

65. **Psilomelane.** Hydrous oxide of Mn, Ba, and K. *Flame*—Barium. *Bor.* and *Micr.*—Manganese reactions. *Cl. tube*—Water.

Add.—Soluble in $H\,Cl$; chlorine evolved, known by its smell. Barium sulphate is usually precipitated on addition of $H_2\,S\,O_4$. **Manganite** ($H_2\,Mn_2\,O_4$) is often crystallised, and yields no barium.

66. **Pyrargyrite.** $Ag_3\,Sb\,S_3 (= 3\,Ag_2\,S \,.\, Sb_2\,S_3)$. Like proustite, with antimony in place of arsenic. *Ch.*—Silver oxide encrustation on antimony oxide. *Add.*—Streak purplish-red (*Miers*).

66*a*. **Pyrite** (see **Iron Pyrites**).

67. **Pyrolusite.** $Mn\,O_2$. *Fus.*—Infusible. *Bor.* and *Micr.*—Manganese reactions. *Cl. tube* — Commonly a little water. Evolves oxygen, a glowing splinter of wood inserted in tube being re-kindled as each puff of gas arises. *Add.*—Soluble in $H\,Cl$ with evolution of chlorine, which is known by its smell.

68. **Pyromorphite.** $3\,Pb_3\,P_2\,O_8 + Pb\,Cl_2$. *Flame*—With sulphuric acid, phosphorus reaction, the green flame surrounding an inner blue one due to lead. *Fus.*—Very easy. *Micr.*—With copper oxide, chlorine reaction. *Ch.*—White lead chloride encrustation; nearer assay, lead ditto. In R. F., metallic lead.

69. **Pyrrhotine.** $Fe_7\,S_8$ $(= 6\,Fe\,S \,.\, Fe\,S_2)$. *Fus.* — About 2. *Bor.* and *Micr.*—Iron reactions. *Cl. tube*—Scarcely any sulphur. *Add.*—Soluble in $H\,Cl$; evolves $H_2\,S$ on boiling. Magnetic before reduction, and attracts its own powder. See **Iron Pyrites.**

70. **Quartz.** $Si\,O_2$. *Fus.* — Infusible. *Micr.* — Undissolved. *Ch.*—Fuses readily with soda; cobalt nitrate added to the product produces a deep blue glass, as in ordinary fusible silicates. *Add.*—Hardness = 7; specific gravity only 2·65.

71. **Redruthite** (**Copper Glance**). $Cu_2\,S$. *Flame*—With $H\,Cl$ copper flames. *Fus.*—About 1·5. *Bor.* and *Micr.*—Copper reactions. *Cl. tube*—No sulphur. *Ch.*—With soda, or when roasted in O. F., metallic copper. With soda, sulphur reaction. *Add.*—Sectile.

72. **Rhodonite.** $Mn\,Si\,O_3$. *Fus.*—About 2·5. *Bor.* and *Micr.*—Manganese reactions. In latter, silica. *Add.* — With $H\,Cl$ commonly effervesces, through presence of some carbonate, but is only slightly decomposed.

73. **Rock-salt.** $Na\,Cl$. *Flame*—Intense sodium. *Fus.*—About 1. *Micr.*—With copper, strong chlorine reaction (p. 61). *Add.*—Soluble in water. Taste characteristic, but similar to sylvine.

74. **Rutile.** $Ti\,O_2$. *Fus.*—Infusible. *Bor.* and *Micr.*—Good titanium reactions. Barely soluble in latter. *Ch.*—The soda-residue, boiled with tin in $H\,Cl$, gives a strong titanium reaction upon standing.

75. **Sal-ammoniac.** NH_4Cl. *Fus.*—Swells up and volatilises without fusion. *Micr.*—With copper oxide, chlorine reaction. *Cl. tube*—Volatilises, forming dense white sublimate and fumes. *Add.*—Evolves ammonia, known by its smell, when pounded up or fused with sodium carbonate. Soluble in water.

75*a*. **Siderite** (see **Chalybite**).

76. **Smaltine.** (Co, Fe, Ni) As_2. Graduates into chloanthite; richer in cobalt (see **Chloanthite**).

76*a*. **Smithsonite** (see **Calamine**).

77. **Soda-Nitre.** $NaNO_3$. *Flame*—Strong sodium. *Fus.*—Very easy. *Cl. tube*—Fused with bisulphate of potash, gives off brown fumes, well seen on looking down tube. *Ch.*—Flares up like nitre. *Add.*—Soluble in water. Saline taste.

78. **Sphene.** $CaSiTiO_5$. *Fus.*—Fairly easy. *Bor.* and *Micr.*—Titanium reaction. Silica in latter. *Ch.*—The soda-residue, boiled with tin in H Cl, gives a clear titanium reaction.

79. **Spinel.** (Mg, Fe) $(Al_2, Fe_2) O_4$. *Fus.*—Infusible, thus differing from similarly coloured garnets. *Add.*—Specific gravity less than zircon (about 4·0 and 4·5 respectively). See notes on **Zircon.**

79*a*. **Stibnite** (see **Antimonite**).

79*b*. **Stream Tin** (see **Cassiterite**).

80. **Strontianite.** $SrCO_3$. *Flame*—Strong strontium. *Add.*—Effervesces in cold H Cl. Even very dilute solutions give, on standing, a precipitate with sulphuric acid. Compare with aragonite or calcite, and see p. 36.

81. **Sulphur.** S. *Flame*—Burns with a blue flame. *Cl. tube*—Volatilises, giving sulphur sublimate.

82. **Sylvine.** K Cl. *Flame*—Strong potassium; otherwise like rock-salt.

83. **Talc.** $H_2Mg_3Si_4O_{12}$. *Fus.*—Infusible. The lamellæ bend away from one another during heating. *Micr.*—Silica. *Cl. tube*—A little water. *Ch.*—With cobalt nitrate, a fair magnesia reaction. *Add.*—Hardness clearly less than that of micas.

83*a*. **Tinstone** (see **Cassiterite**).

84. **Titanic Iron Ore** (**ilmenite** and titaniferous magnetite). **Ilmenite** = $m\,TiFeO_3 + n\,Fe_2O_3$. *Fus.*—Practically infusible. *Bor.*—Iron reactions. *Micr.*—Iron and titanium. *Ch.*—In R. F. magnetic residue. The soda-residue, boiled with tin in H Cl gives a satisfactory titanium reaction. Some specimens are magnetic before reduction.

85. **Topaz.** $(F, HO)_2 Al_2 SiO_4$. (See Groth, *Tab. Uebersicht*,

1898, p. 116.) *Fus.*—Infusible. *Micr.*—Silica. *Ch.*—With cobalt nitrate, alumina reaction. *Add.*—Fused on glass slip as described on p. 62, dulls and etches the surface. Distinguished from quartz by hardness = 8, specific gravity = 3·5, and presence of good cleavage (basal).

86. **Tourmaline.** For composition, see p. 183. *Flame*—Some specimens give boron flame when fused with fluor-spar and bisuphate of potash. *Fus.*—Various, but often easy. *Micr.*—Silica. *Add.*—Distinguished from hornblende by hardness = 7, and very common occurrence of trigonal prisms.

87. **Vivianite.** $Fe_3 P_2 O_8 + 8 H_2 O$. *Flame*—With sulphuric acid, phosphorus. *Fus.*—Easy. *Bor.* and *Micr.*—Iron reactions. *Cl. tube*—Becomes white; gives off water. *Ch.*—Magnetic residue. *Add.*—Soluble in H Cl. Reduces the ammonium molybdate solution, the blue colour mingling with the yellow precipitate due to phosphoric acid. Blue colour characteristic, but alters to brown, becoming then red by transmitted light. Blue crystals strongly pleochroic.

88. **Websterite.** $Al_2 S O_6 + 9 H_2 O$. *Fus.*—Infusible. *Cl. tube*—Much water. *Ch.*—With cobalt nitrate, fine alumina reaction, With soda, sulphur reaction. *Add.*—Soluble in H Cl. Specific gravity = 1·66. **Alunite** ($K_2 Al_6 S_4 O_{22} + 6 H_2 O$) has higher hardness and specific gravity, and is insoluble in H Cl.

89. **Witherite.** $Ba C O_3$. *Flame*—Barium. *Fus.*—2. *Add.*—Effervesces in H Cl. (See also p. 36.)

90. **Wolfram.** (Fe, Mn) $W O_4$. *Fus.*—Decrepitates, but fuses about 3. *Bor.*—Iron and sometimes manganese. *Micr.*—Iron and tungsten. *Ch.*—The soda-residue, boiled with tin in H Cl, gives a fine tungsten reaction. *Add.*—Carbonate of soda bead gives manganese reaction. Lustre and cleavage characteristic.

91. **Wollastonite.** $Ca Si O_3$. *Flame*—Fine calcium with H Cl. *Fus.*—About 4; glows strongly. *Micr.*—Silica. *Add.*—Gives a silica-jelly with H Cl. Some carbonate often present.

92. **Zinc-Blende (Blende).** Zn S. *Fus.*—About 6. *Cl. tube*—Thin sulphur. *Ch.*—Zinc encrustation, at times excellent with cobalt nitrate, poor in other examples; best produced when specimen is in R. F. Some varieties give cadmium encrustation. Often magnetic residue. With soda, sulphur reaction. *Add.*—Soluble with effervescence in hot H Cl, sulphuretted hydrogen being evolved.

93. **Zircon.** $Zr Si O_4$. *Fus.*—Infusible. *Ch.*—The soda-residue, after thorough fusion, treated in a dish with hot water, gives abundant minute hexagonal platy crystals (zirconia) and

rhombohedra (? sodic zirconate). Examine on glass slip under microscopic power magnifying about 400 diameters. For discussion of this reaction, see Lévy & Lacroix, *Minéraux des Roches* (1888), p. 117. If the soda and the zircon are not finely pulverised together and completely fused, a residue of zircon fragments alone appears. See notes on **Garnet** and **Spinel**.

INDEX TO METALLIC COMPOUNDS.

Aluminium, 28, 29, 46, 85, 88.

Antimony, 4, 66.

Arsenic, 22, 26, 48, 55, 64, 76.

Barium, 12, 89.

Bismuth, 13.

Calcium, 2, 5, 7, 17, 31, 34, 40, 78.

Cobalt, 22, 26, 76.

Copper, 11, 14, 24, 27, 30, 53, 71.

Chromium, 23.

Iron, 21, 23, 35, 38, 41, 44, 45, 50, 52, 54, 55, 69, 79, 84, 87, 90.

Lead, 1, 20, 36, 68.

Magnesium, 15, 31, 33, 51, 79.

Manganese, 65, 67, 72, 90.

Mercury, 25.

Molybdenum, 56.

Nickel, 22, 48, 76.

Potassium, 59, 82.

Silver, 8, 47, 64, 66.

Sodium, 29, 73, 77.

Strontium, 19, 80.

Tin, 18.

Titanium, 74, 78, 84.

Tungsten, 90.

Uranium, 63.

Zinc, 16, 35, 42, 92.

Zirconium, 93.

SILICATES.

3, 6, 10, 24, 32, 37, 42, 43, 46, 49, 57, 58, 60, 61, 62, 78, 83, 85, 86, 91.

CHAPTER VIII.

QUANTITATIVE FLAME-REACTIONS OF THE FELSPARS AND THEIR ALLIES.

PROF. SZABÓ of Budapest, by making more precise certain flame-reactions indicated by Bunsen, developed in 1876 a new method for the determination of the felspars and allied silicates found in common rocks.* Practice has again and again shown that the

* "Ueber eine neue Methode die Feldspathe auch in Gesteinen zur bestimmen." Franklin-Verein, Budapest.

An abstract occurs in *Proc. American Assoc. for Advancement of Science*, vol. xxxi., 1882, without illustrations.

observations made in this manner in the Bunsen-flame are as reliable as they are simple and expeditious. Gas is required, but a careful observer working on typical minerals with a blast-lamp might no doubt profitably construct a table of reactions with which to compare the results given in the same flame by undetermined specimens.

The Bunsen-burner used by Szabó has a tube of 1 cm. diameter. A three-rayed support, screwed on over the upper end until it rests 3 cm. below the orifice, carries a removable iron cone 6 cm. high, 5·3 cm. in lower diameter, and 3 cm. in diameter above.

The flame is 13 to 14 cm. high when the cone is not employed. The position of highest temperature, the *fusion-place*, is about one-fourth of the total height of the flame above its base.

The particle of felspar or other mineral to be tested must be of a fixed bulk and about this size • when fused to a globule; it must be carefully selected from a roughly powdered sample of the rock of which it forms a part, and must not be touched by the finger nor immersed in water that is not distilled. The lens should, as usual, be used in the selection of such fragments, and the character of their cleavage can often be noted as a preliminary. Should the mineral fly to pieces in the flame, Szabó recommends that a sample of the mineral should be allowed to decrepitate by heating in a closed tube, the fragment finally used being selected from the material thus already broken up.

The particle is supported on a platinum wire of about this thickness ———, of which 1 decimetre should weigh only 32 milligrammes. The usual small loop is made at the end of the wire.

To secure the particle on the wire, a matter which some workers have found troublesome, but which need cause little annoyance considering the ease with which the observations are finally made, Szabó's directions should be carefully followed. Dip the wire loop in distilled water and touch the granule with it, quickly raising it, so that only the upper surface becomes wetted; turning the wire, the dry surface of the particle comes upwards. Bring it in this position gradually near to the base of the Bunsen-flame, the water thus drying off slowly; a card should be held beneath the specimen to catch it if it becomes shaken off. Finally let it enter the flame and remain there for two seconds, the surface in most cases becoming fused to the platinum wire. The wire can be supported in various ways in the flame, the points selected being in the outer envelope at (a) the base of the flame, (b) at 5 millimetres above the base, and (c) the fusion-

place, about 5 mm. above the top of the iron cone. The present writer has described the following support as one that practice has shown to be useful.* (Fig. 9.)

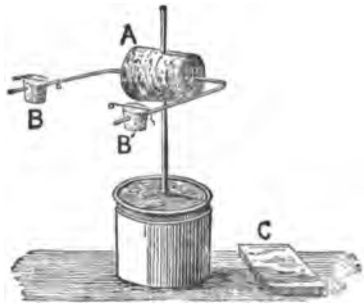

Fig. 9.

A small gallipot, such as is used for Liebig's extract, forms a base that is clean, strong, and adequately heavy. A brass wire, about 3 mm. in diameter, passes through the cork of this, and rises 15 centimetres above it, carrying a stout cork **A**, which can be slid up and down to any level. A steel wire or knitting-needle, some 25 cm. long, is pushed horizontally through **A**, the last 7 cm. on either side being then bent forward at right angles. Two small corks, **B** and **B′**, are carried by the parallel arms thus formed, and support, by means of a knife-slit in the top of each, the fine platinum wires employed. **B** can be slipped off the steel wire, the mineral fragment can be attached, with Prof. Szabó's precautions, to the platinum loop, and the carrier replaced without fear of loss by jarring. **B′** can be used for a type-specimen to be compared with that under examination, the wires on both corks being adjusted to exactly the same level, and one or other being brought at will into the flame.

The cork **A** being set approximately at the proper height, the rotation of the steel wire within it moves **B** and **B′** equally in vertical planes, and gives a delicate means of fine adjustment. To secure uniformity of position in successive experiments, the platinum loop carrying the specimen is brought to the exact level of the top of the Bunsen-burner, or to the level of the top of the iron cone. A small plate of wood, **C**, of the thickness of 5 mm.,

* "On a simple apparatus for flame-reactions." *Geological Magazine*, 1888, p. 314.

is then slid under the gallipot, the specimen being thus raised to the positions adopted by Prof. Szabó, without any of the difficulties that often arise from the jarring or stiffness of motion in more elaborate supports.

The dimensions above given are those adapted to a Bunsen-burner of ordinary height and ordinary diameter of base. For packing, the erection can be taken down, and the 5-millimetre plate and the smaller corks can be kept inside the gallipot till required.

Observation of Fusibility. — This forms the least reliable part of Szabó's reactions, as a temperature slightly under that of his standard flame makes the species seem equally difficult to fuse. The scale is unfortunately numbered in the reverse order to that of von Kobell. It is here simplified; the numbers refer to the result obtained, whatever part of the flame is used; thus, a mineral may have a fusibility of 1 in the point b and of 3 in the point c. The product must be examined with a lens.

0. Infusible.
1. Edges and corners alone rounded.
2. General form unaltered, but edges, corners, and faces fused.
3. Form altered, but not to a globule.
4. Fuses to a globule.

The *time of heating* is in each observation one minute, the specimen being tried first in the position a (base of flame), then moved to b (5 mm. above the base), then to c (5 mm. above the iron cone), notes being made of its appearance on withdrawal from each portion of the flame.

Determination of Sodium and Potassium.—Held in position b (first row, fig. 10), the assay imparts a certain degree of colouration to the flame. Five degrees are recognised, No. 5 being the most intense. The observer, with a drawing of these degrees before him, notes down the figure corresponding to the flame given by his assay, and picks up an indigo prism or cobalt glass 5 mm. thick, through which he views the flame with the object of detecting potassium. Three degrees of the characteristic violet-red flame may be distinguished by a good eye (lowest row, fig. 10). All this can be done in the one minute assigned to the observation; at its expiry the wire is withdrawn and the degree of fusion also noted.

The cone is put on and the same assay brought to c, the fusion-place. In one minute similar observations of sodium

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(second row, fig. 10) and potassium (lowest row, fig. 10) are made, and the fusibility is again observed. The colourations

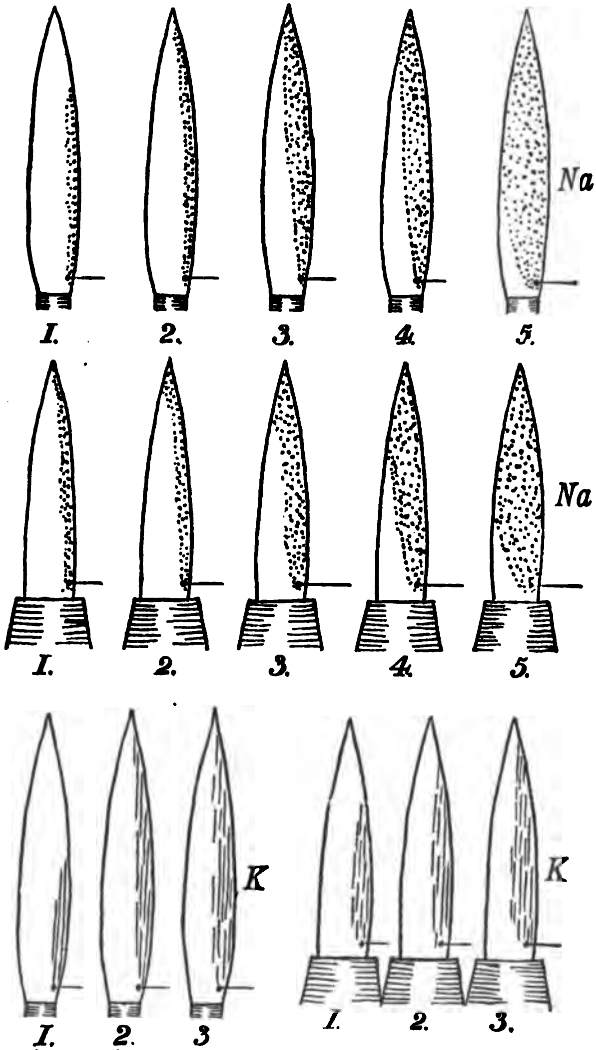

Fig. 10.

should be slightly stronger than in b, the degree 3, for instance, now representing an intenser flame than 3 in the previous observation.

The assay is now dipped in distilled water and then into powdered gypsum, which thus adheres to and surrounds it. On reheating in position c, the gypsum assists decomposition, the sodium and potassium being converted into sulphates. The observation should be made when the assay has been two minutes in the flame.

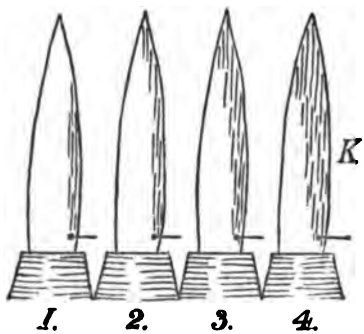

Fig. 11.

It is unnecessary to observe the sodium reaction except as a check; but the potassium flame is intensified and four degrees are distinguishable (fig. 11), No. 1 representing a quantity too minute for previous detection. See, however, p. 85.

Determination of Calcium.—The lime in felspars and allied minerals can generally be inferred from the diminution of the soda and potash; but its flame may be seen as follows:—

Put fragments of the mineral in a glass tube with cold concentrated hydrochloric acid sufficient to completely cover them. Close with wax and leave for 24 hours. Then open and plunge in a fairly thick platinum wire, coiled at the end. The drop thus brought out is held in position b, and the first colour observable is due almost entirely to the calcium. A direct-vision spectroscope shows the red, orange, and green lines distinctly. The flames due to sodium, potassium, and lithium follow in order, and the degrees observed during this operation often serve to distinguish minerals in which the actual percentage of soda, &c., is the same, a higher degree being shown by those more easily decomposed by acid.

TYPICAL REACTIONS.

MINERALS.	In position b. Time 1 minute.			In position c. Time 1 minute.			In position c with Gypsum. Time 2 minutes.	Drop of the H Cl solution, after digestion of particles for 24 hours. Position b.		
	Na.	K.	Degree of fusion.	Na.	K.	Degree of fusion.	K.	Ca.	Na.	K.
1. **Orthoclase**, .	1-3	2-3	*1-3*	1-3	2-3	*3-4*	3-4	0	1-2	0
2. **Soda-Orthoclase**,	3-4	1	*3-4*	3-4	1-2	*4*	2-3	0	1-2	0
3. **Albite**, . .	5	0	*3-4*	5	0	*4*	0	0	1-2	0
4. **Oligoclase**, .	3-5	0	*2-4*	4-5	0	*4*	1-2	0	2	0
5. **Andesine**, .	3-4	0	*2-3*	3-4	0	*3-4*	1-2	0-1	2-3	0-2
6. **Labradorite**,	2-3	0	*0-2*	2-3	0	*2-3*	1-2	1-2	2-3	0-1
7. **Bytownite**, .	2-3	0	*0-1*	2-3	0	*1-2*	0-1	2-3	1-3	0-1
8. **Anorthite**, .	1-2	0	*0-1*	1-2	0	*0-1*	0-1	2-3	1-3	0-1
9. **Leucite**, .	2-3	3	*1*	2-3	3	*2*	4	0	2-3	4
10. **Nepheline**, .	5	1-3	*2-3*	5	2-3	*3-4*	3-4	0	5	3-4
11. **Nosean**, .	5	1	*1*	5	1-2	*2*	2-3	0	5	3
12. **Haüyne**, .	5	1-2	*1*	5	1-3	*2-3*	2-3	0-3	5	1-3
13. **Sodalite**, .	5	0-3	*1-3*	5	0-3	*3-4*	0-3	0-1	5	1-3

A table based on those prepared by Szabó is given above. The degree of fusion is stated according to the modified scale adopted on p. 81. The observer draws up a blank form on the same lines, notes into it each observation numerically as soon as made, and compares the whole result with the series given in the table. A good plan is to take each result separately and write down all the felspars or allied minerals to which it might possibly correspond. A comparison of the brief lists thus formed enables one to pick out the name that occurs most frequently, or the two

between which the mineral must lie. These reactions, performed upon minute grains, and occupying altogether about ten minutes, have a great value to the geologist, however simple they may at first appear to the chemist, mindful of his refined but lengthy methods of analysis.

The determination of potassium in the flame is rendered easier by the following process,* which allows of a complete decomposition of the silicate, and which is unaffected by the presence of a bright sodium flame. On a loop of platinum wire, 2 mm. in diameter, form a bead of sodium carbonate, and view the flame given by it through 5 mm. of blue glass to see that no potash is present. Moisten this with water, and pick up about 2 cubic mm. of the mineral—*i.e.*, about twice as much as is used in Szabó's process. Place the wire on the support in the position c, 5 mm. above the cone. The specimen does not tend to fall off, but is soon attacked and dissolved. Leave for two minutes by the watch.

Then observe the flame through 5 mm. of blue glass. The bright sodium flame is cut off, except for a marginal column, which comes through blue. If potassium is present, it is revealed by a pink-violet inner fringe to this blue column. Judging from its extent and also its intensity near the assay, three grades can be established.

Grade 1 = about 4 per cent. of potash.
,, 2 = ,, 8 ,, ,,
,, 3 = ,, 12 ,, ,,

The ease of manipulation in this method, and the completeness of decomposition, seem to recommend it. It is also of service in examining the glassy or fine-grained groundmasses of igneous rocks. All true orthoclases fall in grade 3; but each observer should establish the grades for his own eye upon specimens already known.

CHAPTER IX.

EXAMINATION OF THE OPTICAL PROPERTIES OF MINERALS.

In a book written for the geologist rather than for the mineralogist, a detailed account of the optical properties of minerals, as observed in slices cut from them in known directions, would be out of place. The appearance of the common rock-forming minerals in

* G. Cole, "Potassium in Silicates," *Geol. Mag.*, 1898, p. 103.

ordinary microscopic sections is stated in Chapters xvi. and xvii. It will be well, however, to indicate at once some of the terms that may be employed in describing the phenomena then observed.* It has long been customary to introduce into these terms the hypothesis of an incompressible ether, of elasticity variable with the direction of its displacement; but, as Mr. Fletcher has pointed out, changes of view as to the nature of the ether have rendered such phraseology undesirable.

If we take a plate cut from a doubly refracting crystal, but not perpendicular to an optic axis, and cause a ray of ordinary light to strike it in a direction perpendicular to its surface, this ray, on entering the crystal-plate, is split into two, which respectively vibrate in planes that are perpendicular to one another. The traces of these two planes on the surface of the plate may be called the **vibration-traces** for that particular section. They have also been styled the "vibration-directions," and "directions of greatest and least elasticity," for that particular section.

The ray corresponding to one of these traces is propagated with greater velocity than that corresponding to the other trace. We may call one trace, then, the **fast-ray vibration-trace**, and the other the **slow-ray vibration-trace**†, or "fast-ray trace" and "slow-ray trace" where shortness is desirable. These correspond to Prof. Groth's "vibration-direction of greater light-velocity," and "vibration-direction of less light-velocity;" and to the n'_p and n'_g of MM. Michel Lévy and Lacroix‡, who distinguish the directions as those of rays with smaller or greater refractive index respectively.

It is of interest to observe that the vibration-traces represent the directions of the axes of the ellipse which is formed by the intersection of the plane of our crystal plate with the optical indicatrix, or surface of reference for rays propagated in any direction in the crystal. The vibration-trace of the slow ray corresponds to the long axis of this ellipse (n'_g)§, and *vice versâ*, and the lengths of the two axes are proportional to the refractive indices for rays of the same colour vibrating parallel to them respectively, and travelling normally to the surfaces of the plate.

* For a discussion of the principles underlying the optical properties of minerals, the reader should specially consult Fletcher's *Optical Indicatrix* (*Min. Mag.*, vol. ix., 1881, p. 278; also issued as a separate work, revised, published by H. Frowde, 1892); also Miers, *Mineralogy*, 1902, and Groth, *Physikalische Krystallographie*, 3rd or later edition.

† I am indebted to Mr. L. Fletcher, F.R.S., for generous help in the discussion and selection of the above terms.

‡ *Les Minéraux des Roches*, pp. 3 and 4.

§ Or, as Mr. Fletcher mnemonically puts it to me, the longer trace is the longer-time vibration-trace

The indicatrix of a biaxial crystal is an ellipsoid, the three axes of which, perpendicular to one another, have different lengths; it has three planes of symmetry, each of which contains two of the axes, and is perpendicular to the third axis. If a ray of light is propagated along a line, other than an optic axis, lying in one of these planes of symmetry, it travels with one or other of two different velocities. In one case the ray vibrates perpendicularly to the plane of symmetry, and therefore parallel to the axis which is perpendicular to that plane; the vibration-direction in the other case is parallel to the plane of symmetry. The velocity of the former ray is constant, in any particular crystal, whatever the direction of propagation of the ray may be within the plane of symmetry; its refractive index is also constant, and it is, in this respect, an "ordinary" ray.

There are, however, three different indices of refraction for the three ordinary rays that correspond to the three planes of symmetry respectively. Seeing that rays of the various colours composing white light suffer refraction in different degrees, these indices are determined with monochromatic light, the sodium flame being generally used. They are styled the **principal indices of refraction** of the crystal. The smallest is usually designated α, or n_p of French authors; the mean is β, or n_m; and the greatest is γ, or n_g. Since the value of β is not the arithmetic mean between α and γ, the result of $\frac{\alpha + \beta + \gamma}{3}$ is employed to express the *average* refractive index of the mineral. This may be briefly termed the "refractive index of the mineral." A very high refractive index for rock-forming minerals is 2·712, that of rutile; while 1·433, that of fluor-spar, is a low refractive index.

By definition, the axes of the optical indicatrix of a biaxial crystal are proportional to the principal indices of refraction; the length of the shortest axis is thus expressed by α or n_p, that of the mean axis by β or n_m, and that of the longest by γ or n_g.

In the case of a doubly refracting biaxial crystal, there must be one section in which the difference in the velocities of the slow ray and the fast ray, travelling perpendicularly to the faces of the plate, is as great as possible for that particular mineral; such a section contains the longest and shortest axes of the optical indicatrix. Consequently, the fast ray for this section will be the ray of least refractive index in the crystal as a whole; and its direction of vibration will be that of the shortest axis of the indicatrix, the German 𝔞, or the "axis of greatest elasticity" of the older elastic theory. The slow ray for such a section will similarly be the slowest possible ray, or ray of greatest refractive

index, and its vibration-direction will agree with the longest axis of the indicatrix, *i.e.*, with the German $\mathfrak{c}$, or the "axis of least elasticity" of the older elastic theory.

In uniaxial crystals—*i.e.*, crystals of the HEXAGONAL and TETRAGONAL systems—any section parallel to the principal axis (optic axis) of the crystal contains these two directions, one of which corresponds to the principal axis, and the other to any line perpendicular to it; and such a section is required in describing the optical properties of a mineral of either of these systems.

If the principal axis is the vibration-direction for the slowest ray, the crystal is called *positive;* if for the fastest ray, it is called *negative*.

In biaxial crystals, the section containing the longest and shortest axes of the indicatrix is always the plane of the optic axes. Two of the axes of the indicatrix bisect the acute and obtuse angles between the optic axes, and are therefore styled the *acute* and *obtuse bisectrices* respectively; they are necessarily perpendicular to one another. If the vibration-direction for the slowest ray bisects the acute angle between the optic axes, the crystal is called *positive;* if this angle is bisected by the vibration-direction of the fastest ray, the crystal is called *negative*.

In crystals of the RHOMBIC system, the axes of the indicatrix are coincident in direction with the crystallographic axes, and the optic axial plane is parallel to one of the three planes of symmetry of the crystal. The vibration-directions for the slowest and fastest rays correspond to those of the two crystallographic axes that are contained in a section parallel to the optic axial plane. The third axis, perpendicular to the plane of this section, is the French n_m, the German $\mathfrak{b}$, and the "axis of mean elasticity" of the older elastic theory. For the section containing $\mathfrak{b}$ and $\mathfrak{a}$, $\mathfrak{b}$ will coincide with the slow-ray vibration-trace; but for that containing $\mathfrak{b}$ and $\mathfrak{c}$, $\mathfrak{b}$ will coincide with the fast-ray vibration-trace.

In crystals of the MONOCLINIC system, the optic axial plane is either parallel to the plane of symmetry—*i.e.*, to the clinopinacoid —or is some plane perpendicular to this. In the former case, the bisectrices make angles with the vertical crystallographic axis, which vary for different mineral species. In the latter case, one of the bisectrices, corresponding either to $\mathfrak{a}$ or $\mathfrak{c}$, according to the species, coincides in direction with the orthodiagonal; the other coincides with the trace of the plane of symmetry.

In the TRICLINIC system, there is no relation between the axes of the optical indicatrix and those of crystallographic form.

The terms, as applied to crystal-sections, may now be summed up as follows :—

Fastest-ray vibration-trace = direction of vibration for rays of least refractive index and greatest velocity, the direction of propagation being perpendicular to the section ; = "axis of greatest elasticity." Symbol $\mathfrak{a}$, α, or n_p.

Slowest-ray vibration-trace = direction of vibration for rays of greatest refractive index and least velocity, the direction of propagation being perpendicular to the section ; = "axis of least elasticity." Symbol $\mathfrak{c}$, γ, or n_g.

It should be remembered that the two latter symbols in each case represent actual numbers, which are the refractive indices for rays vibrating parallel to the directions for which they respectively stand.

While the applications of the optical properties of minerals will be dealt with in connection with the microscope (pp. 141 to 153), yet one important property may be treated here, since it can be observed in ordinary specimens, without the use of sections. This is the phenomenon of pleochroism.

Pleochroism.—Several minerals which are coloured and yet fairly transparent exhibit their pleochroism in ordinary crystals. When held up between the eye and the light, either in the fingers or cemented to a little stick, and turned about in various directions, a change of tint may be perceptible according to the direction in which the light traverses the crystal. Vivianite and transparent andalusite can easily be examined in this way.

The extreme colours thus observed are the "face-colours" (*Flächenfarben*) of Haidinger ; but the "axis-colours" (*Axenfarben*) prove with more certainty that a mineral is pleochroic and enable one to correctly describe its characters. The colour of any face is, in fact, compounded of the colours of two groups of rays into which the light entering the crystal has been divided. Brewster* in 1819 passed polarised light through a number of specimens, noting the extreme differences of tint produced by bringing different directions in the crystal parallel to "the plane of primitive polarisation." This is the method now made use of in observing the axis-colours of minerals in microscopic sections (see p. 143). Haidinger,† however, by his **Dichroscope** (*dichroskopische Loupe*), made both the axis-colours

* *Phil. Trans. Roy. Soc.*, 1819, p. 11.

† *Abhandl. böhm. Gesell. der Wissenschaften*, v. Folge, Band 3 (1844); reprinted in *Poggendorff's Annalen*, Bd. lxi., p. 302. See also *Pogg. Ann.*, lxv. (1845), p. 4.

visible at once. This instrument can be easily obtained, is very portable, and proves in many cases valuable in the examination of transparent minerals, such as gems.

A brass tube, some 6 cm. long, encloses a cleavage-prism of calcite, the longer edges parallel to the axis of the tube. On each end of the calcite is cemented a small glass prism of about 18°, which makes the terminal surfaces vertical and prevents the rays from being so strongly refracted as to necessitate a stouter instrument. Prof. Church states that as an alternative method the ends of the calcite may be cut off perpendicular to the longer edges.

At one end of the tube is a magnifying lens, at the other a small square aperture, the image of which is sharply seen through the lens. But this image is doubled by the calcite; and, if a pleochroic mineral is held against the aperture, the two squares seen will be of different colours. The mineral must be viewed in some direction other than that of an optic axis, and must be turned about until the maximum difference of colour is observable in the two images of the square, in which case the vibration-traces of the two groups of rays emerging from the crystal-face are parallel to those of the calcite rhombohedron. Consequently the rays of one group are already vibrating parallel to one of the planes into which the doubly-refracting calcite would tend to bring them; these rays therefore are not doubly refracted by the calcite, but come through to the eye entirely in one of the two images formed. Similarly the other set of rays from the crystal, being at right angles to the first, comes through entirely in the other image formed by the dichroscope. Thus the colours due to each set are completely separated for examination, and this will again occur on rotation of the dichroscope through 90°.

It will be remembered that uniaxial crystals are *dichroic* and biaxial are *trichroic*. Thus, if a prism of beryl or tourmaline is rotated about its longer axis, no change of face-colour will be perceptible to the eye, and, a far surer test, the colours of the two squares seen with the dichroscope remain respectively the same and at their maximum difference. But if a biaxial crystal, such as topaz, is thus examined, changes will take place in the axis-colours as different faces are viewed. Such observations should, however, be conducted on cylinders or on sections of equal thickness, and the complete determination of the character of the pleochroism of a particular mineral is beyond our present aim. But the mere fact that a mineral is pleochroic is often of considerable value. Thus garnet and red spinel may be dis-

tinguished from ruby, minerals of the cubic system being optically similar in all directions, and consequently exhibiting no pleochroism, while ruby gives pink-red and yellow-pink axis-colours. Glass imitations of emerald, ruby, or sapphire may be similarly detected, and this too in cases where the nature of the specimen renders other tests undesirable.

Dr. Lang has fitted a cap to the end of the dichroscope that bears the aperture, capable of rotation in various directions. The mineral is fixed by wax to the aperture in this cap, and can thus be oriented in regard to the instrument (Groth, *Krystallographie*, ed. 3, p. 154).

We may note in conclusion that Haidinger's first experiments were conducted with a plain cleavage-prism of calcite, at one end of which a stop with a square opening was placed; and such a prism, costing a few pence, and a card with a hole cut to suit, so that the two images fall side by side, serves all purposes of ordinary observation or demonstration. The dichroscope can now be obtained from London mineral-dealers or opticians, at prices varying from about 15 to 20 shillings.

PART III.

THE EXAMINATION OF ROCKS.

"As for the earth, underneath it is turned up as it were by fire. The stones thereof are the place of sapphires, and it hath dust of gold."—*The Book of Job.*

"No arrangement can pretend to define and separate those objects which the hand of nature has neither defined nor separated."—JOHN MACCULLOCH, *A Geological Classification of Rocks*, 1821.

CHAPTER X.

INTRODUCTORY.

WHILE a mineral may be to a large extent discussed and determined in the laboratory, a rock, considered as a part of the earth's crust, and not as a mere aggregate of chemical compounds, requires a very full knowledge of its mode of occurrence before it can be properly treated of and described. In fact, after a study of a number of type-specimens, the student is recommended to go out to some well-described district, and to endeavour to recognise the varieties of igneous and sedimentary rocks by careful observation in the field. In this way alone can he appreciate the various modes of weathering, the massive or minuter structures due to jointing, the smooth or rugged outlines, that characterise the masses of which his hand-specimens form a part. He will meet with many difficulties of determination, and will procure a store of well-selected material on which to work during less propitious days. Questions will arise, even during microscopic examination, that will send him back to gain further information in the field; and in the end his investigations will have far more geological value to him than any knowledge gathered in type-collections or museums.

The notes that follow presuppose that the specimens have been collected in the field; that at any rate something is known about

their mode of occurrence and their relation to other parts of the same mass. Weathered specimens should be avoided as a rule, but often reveal structures hidden in the unaltered portions. Collections made from stream-beds or taluses are often useful for showing the general character of a district; but rocks so gathered are seldom of value for detailed study. Nothing short of striking the rock-mass *in situ* with the hammer, and taking in with the eye its position and surroundings, even to the broader features of the landscape, should content the geologist who would follow worthily the founders and masters of the science.

The points of interest presented by various types of rock will be dealt with later. Broadly speaking, in the case of sedimentary rocks specimens should be collected showing weathered surfaces and also freshly exposed bedding-planes, since minute structures, fossils, &c., are best made out by a comparison of these. In the case of igneous rocks, specimens must be taken from the centre and from the edges of any dyke or lava-stream, and contact-phenomena repay the closest examination.

The pocket-lens and the knife are, in the field, of paramount value. To one, moreover, familiar with microscopic sections, a number of structures and mineral-forms will reveal themselves with unexpected clearness when a fairly smooth surface of the rock is examined with the lens alone. The pocket-knife must be used freely, as in the case of minerals, in estimating the hardness of a rock. The angle of a steel hammer, drawn across the face, often gives similar information. All rocks tend, however, to have a hardness a little below that of their principal constituents, owing to looseness of texture or development of decomposition-films between the grains. But granular limestones can at once be distinguished by the knife from the unscratchable quartzites; basalt, which is scratched with some difficulty when fresh, can in this state never be confused with black limestone or compact dark shale—mistakes that have been often made during the hurried examination of hand-specimens. The acid-bottle, owing to risk in carrying and the necessity of employing heat in many tests, is seldom of great advantage in the field, though in the laboratory it should always be at hand. Dry citric acid, as already described, may, however, be conveniently carried on excursions.

CHAPTER XI.

ROCK-STRUCTURES EASILY DISTINGUISHED.

THE structure of a rock naturally demands the first attention. In the majority of cases evidence can be obtained in the field respecting the mode of origin of the specimens collected, and only their systematic position will remain to be determined. Rocks may be divided according to their more obvious structural characters into the following groups:—

GROUP A.—COARSELY FRAGMENTAL ROCKS.

Stratification may or may not be present. In gravels and con glomerates current-bedding should be looked for. The position of the pebbles, with their longer axes lying in planes parallel to one another, will often give a clue to the bedding or the local dip. The degree of rounding of the pebbles, their average size, and any evidence of crushing and recementing that they may have undergone since their deposition, are structural points that may prove of considerable value.

If the fragments forming the rock are very angular, we may be dealing with an old talus unworn by water, with a volcanic agglomerate, or with a mass brecciated subsequently to its consolidation. The nature of the fragments will probably decide the first and second cases; in the third, we must search for slickensided surfaces, which should be abundant, and must study the relations of the fragments one to another. If the rock is a friction-breccia, detached portions of larger blocks will be found lying suggestively near their parent masses, the interspaces being filled with a sort of fault-rock. Other blocks will be faulted without being actually broken asunder; but there are, of course, cases, especially of fragmental rocks that have been affected by earth-movements, which are particularly hard to settle. Near faults, in contorted mountain-districts, and especially where softer rocks abut against harder and more resisting masses, this brecciated structure may be looked for and expected.

GROUP B.—ORDINARY STRATIFIED ROCKS.

The points to be ordinarily examined in these are the character of the bedding, which may be so fine as to produce a laminated

structure; and the degree of coarseness of the constituents. The texture of the rock may thus be granular and grit-like, or quite microgranular and compact. Fine-grained volcanic tuffs and ashes must often be classed with ordinary sediments until the aid of the microscope can be called in. Abnormally large fragments in a rock of fine texture, particularly if they consist of exceptional materials, may often be ascribed to the action of floating ice. Examples of this kind are the granite and other boulders that have been found in chalk.

Oolitic and **pisolitic** structures, the latter, as commonly understood, being a coarse development of the former, are comparatively common among limestones. With a lens, the concentric coats of the egg-like granules can be clearly seen, and often a central nucleus, some fossil or mineral fragment, can be detected in those that have been neatly fractured. On the weathered surfaces of some oolites, such as the Hirnant limestone, the structure is brought out with great distinctness.

On the surface of the stratified layers, **ripple-marks**, casts of sun-cracks and worm-burrows, footprints, and other signs of a littoral origin, may often be detected in the field. The relations of the **fossils** to the bedding-planes must also be observed; in some instances mollusca are found embedded in the position in which they lived in muddy banks; in some beds again, bivalves will be found commonly entire; in others the separation of the valves and the rolling of the fossils generally will give evidence of troubled waters at the time of deposition. Derived fossils must not be overlooked.

The nature of the **cementing** material in a granular rock must be examined. Interesting and exceptional substances, such as barytes, have been occasionally found to play this part.

Concretions must be studied from a mineral stand-point. On being broken open, they often show shrinkage-cracks filled with products of infiltration, giving rise to a **septarian structure**. Fossils and various original structures are often preserved in the concretions when lost by alteration in the surrounding rock.

Lastly, the **joints** must be inspected. They may be filled with secondary minerals, and their bounding surfaces may at times be slickensided by earth-movements.

We must bear in mind that, associated with ordinary fragmental stratified rocks, there often occur bands of crystalline material, such as rock-salt and alabaster, which have been deposited from solution and which exhibit a massive structure.

GROUP C.—CLEAVED AND FOLIATED ROCKS.

Cleavage must be distinguished from lamination, hand-specimens at times leaving this point unsettled. Traces of the original bedding must be keenly looked for, and hard resisting bands or coloured stripes at an angle to the cleavage-planes often afford the necessary evidence. Fossils will sometimes be found distorted on the cleavage-planes. A rippled wavy structure, the herald of foliation, often causes the cleavage to become imperfect.

Foliation consists in the grouping of the mineral constituents along surfaces that are parallel to or follow the curvature of one another. Although the development of minerals, notably mica, along some cleavage-planes connects cleavage and foliation, in many cases the latter structure is due to the rolling out, as in a mill, of previously crystalline materials, so that each fragment assumes the form of a much extended lenticle. Hence it is important to trace, if possible, the passage of a foliated rock into one with normal structure, whether igneous or sedimentary, and too much care cannot be devoted to the question as to what minerals in the schistose product are deformed primary substances, and what have, on the other hand, been developed during the period of crush and pressure.

The resistance of large pre-existing crystals produces the **eye-structure** of many gneisses, the smaller constituents flowing round the larger ones and tailing out in streams on either side. This structure is best seen on surfaces perpendicular to the planes of foliation.

Rarely, but most interestingly, true pebbles remain, uncrushed and recognisable, in foliated rocks, as evidence of their former sedimentary origin; but it must be remembered that the crumpled or extended foliation-planes themselves do not necessarily represent original surfaces of lamination.

GROUP D.—ROCKS THAT HAVE CONSOLIDATED FROM A STATE OF FUSION (IGNEOUS ROCKS).

The relations of these to the surrounding masses will often decide their mode of origin; but in an unfortunately large number of cases the exact contact-plane cannot be examined, and the junction is, indeed, often faulted, owing to the difference in hardness and compressibility of the igneous mass and the adjacent sediments. We may subdivide this extremely varied

group by certain well-marked types of structure. We must premise, however, that in the rocks of any subdivision the constitution may be either approximately uniform throughout, or one or more of the crystalline constituents may be developed on a larger scale than the rest. In the latter case the rock possesses **porphyritic structure** in addition to any other that may be present. A glassy rock with fairly conspicuous disseminated crystals is similarly said to be porphyritic.

Prof. Iddings has styled the obvious porphyritic crystals of a rock **phenocrysts**. Those crystals that have been derived from some other rock, and are foreign to the magma in which they are now found, are called by Prof. Sollas **xenocrysts**.

Columnar structure is also common to igneous rocks of whatever grain. Arising as a phenomenon of contraction, it produces columns in the selvages of volcanic dykes; or the bold examples at the base of massive sills and flows, so conspicuous in the West Highlands or Auvergne; or the yet coarser and less regular columns to be seen in many granitic rocks. The columns, large or small, though typically hexagonal, are often trigonal, rectangular, or pentagonal, or have even seven or eight surfaces of contraction.

The **spheroidal structure**, in which the rock breaks up into roughly or regularly concentric coats, though often developed by mere weathering and exfoliation of the surfaces of jointed blocks or boulders,* is typically due to curved surfaces of contraction. Its coarser type may be seen in granite, and its most delicate type as the perlitic structure of glassy rocks. The "pillow-structure" of some basic rocks is a variety of the spheroidal, arising probably during movement of the lava. The pillow-like masses, fitting into one another, are often more glassy in their outer layers. (See *Quart. Journ. Geol. Soc.*, vol. xlvi., p. 312, and "Silurian Rocks," vol. i., pp. 85 and 431, and plates I. and IV., *Geol. Survey of United Kingdom.*)

Drusy structure ("miarolitic" structure) may also occur in all types of igneous rocks, when crystals, often of great beauty, are developed on the walls of cavities in the mass.

In **banded structure**, the crystals, or masses of differing composition, are carried out by flow into separate bands. This is most commonly seen in glassy rocks, where the spherulites and crystallites are commonly arranged in bands.

Sub-Group 1.—Glassy Rocks.

To the eye, and even to the lens, some igneous rocks appear

* For cases on a large scale, see Branner, "Decomposition of Rocks in Brazil," *Bull. Geol. Soc. of America*, vol. vii. (1896), p. 277.

completely glassy. They are liable to be traversed by minute joints, and occasionally the little blocks into which the rock is divided are again broken up during contraction by beautiful curved rifts, giving rise to the **perlitic structure.** Such rocks were called "Perlstein" early in this century, since the glass becomes divided into little globes, which have, on account of the flaws, a nacreous or pearly lustre. On the smooth surface of master-joints cutting across the rock, the structure reveals itself to the lens as a series of fine lines curving like the fronds of an opening fern. These are often, as in many of the beautiful Tertiary examples from Hungary, marked out by light yellow or brownish lines of iron oxide, the result of incipient decomposition. (See fig. 42.)

Spherulitic Structure.—This arises when the crystallising material separates out from the glass in globular aggregations, which vary from a millimetre to 5 or 6 cm. in diameter, and may even reach the dimensions of 1 metre. A radial structure is often seen in the spherulites, and sometimes they are built up of concentric coats. At other times, particularly in large examples, the centre is hollow, or has become filled with chalcedony or calcite during alteration of the rock. Except in highly altered cases, the spherulites are easily distinguished from the glass, even when little difference can be detected under the microscope. They are lighter and commonly browner in colour, and sometimes become easily detached from the matrix. In highly silicated rocks, they are more easily decomposed than the surrounding glass, becoming occasionally soft and powdery while the matrix remains fresh and lustrous.

Lithophyse-structure.—A comparatively rare form of spherulitic structure. The lithophyses ("stone-bladders") were so named by von Richthofen* from the supposition that their hollows were caused by the expansion of vapours in the interior. The lithophyse looks like a large spherulite, the concentric coats of which are separated from one another by interspaces, in which minute crystals have commonly been developed. In older examples, these hollows have been filled up, as in the case of the large altered spherulites already referred to, so that the lithophyse consists of alternating shells of ordinary lithoidal spherulitic matter and quartz, chalcedony or calcite. Beautiful drawings of the lithophyses of the Yellowstone Park accompany Mr. Iddings's paper on Obsidian Cliff in the *Seventh Annual Report of the U.S. Geological Survey* (for 1885–86), p. 249.

* "Studien aus den ungarisch-siebenbürgischen Trachytgebirgen," *Jahrbuch der k.-k. geol. Reichsanstalt*, 1860, p. 180.

Fluidal Structure.—Though commonly associated with banding, this structure may occur in a simple form when, owing to the motion of the rock, all the crystallites and crystals are carried along with their longer axes parallel to one another. As has often been pointed out, the phenomena produced by the flow of these viscid glassy lavas are reproduced in the structures due to pressure-metamorphism. Like surfaces of foliation, both the bands and lines of flow show frequent involutions and contortions.

Flow-Breccia Structure.—Lavas, especially glassy ones, are often torn to pieces by differential movements during flow; what have been called "agglomerate-lavas" thus arise, with a brecciated structure that causes them in the field to resemble tuffs.

Pumiceous and Scoriaceous Structures.—The rock may be completely glassy, with numerous elongated steam-vesicles, as in pumice; or more lithoidal and less completely vesicular, as in common scoriæ. Such rocks often become **amygdaloidal** (see p. 100).

Sub-Group 2.—Lithoidal Rocks.

In this division we bring together rocks of a "stony" appearance, such as the "lithoidal lavas" of old continental writers, which may or may not contain some glassy matter. All the common "porphyries," as well as most lavas, will fall here, and their further separation must be left to microscopic examination.

Hemicrystalline Structure.—The matrix is compact and often almost vitreous to the eye. The lens will sometimes show spherulites aggregated together, and banded and fluidal structures may appear. Such rocks, consisting of a close admixture of crystallites, crystals, and glass, are often called "cryptocrystalline," and include those with the "microlitic structure" of M. Lévy.

Microcrystalline Structure.—The individual constituents become fairly distinct with the lens, though very possibly not specifically determinable by this means; the microscope reveals no glass. The individual crystals may be mere rounded granules ("microgranular," see later), or "allotriomorphic" (*i.e.*, bounded where they come into contact with their neighbours), or "idiomorphic" (exhibiting their proper outlines). When there is a general tendency to idiomorphism in the first formed grains, while quartz has developed out last and has moulded itself allotriomorphically on the felspars, &c., that have preceded it, we

have the "microgranitic" structure of Lévy.* When, on the other hand, the quartz of this last period of consolidation has also a tendency to form idiomorphic crystals, M. Lévy styles the structure "microgranulitic." The use of a structural term depending on the minerals present must, however, of necessity be somewhat limited.

Scoriaceous Structure occurs commonly in the rocks of this sub-group, and gives rise, when the cavities are filled with alteration-products, to the easily recognised **amygdaloidal structure**. The crystallised secondary minerals forming these ovoid groups or "amygdales" should be extracted and examined independently. Sometimes the apparently solid amygdale is a mere hollow shell, which has checked further infiltration as it developed upon the walls of the cavity.

Sub-Group 3.—Distinctly Holocrystalline Rocks.

These show throughout a crystalline texture, attaining sometimes a great degree of coarseness, with crystals 10 or 15 cm. long.

Granitic Structure.—This repeats the microgranitic on a bold scale, and there is thus the same intermingling of forms tending to show crystal-outlines and of purely allotriomorphic grains. The term has been used by Lévy for both acid and basic rocks; but in the latter series he generally prefers "grenue" for "granitique."

Granular Structure.—M. Lévy, employing "granulite" in a limited sense,† uses the name "granulitic structure" for a fine-grained aggregation of well individualised and even idiomorphic crystals, quartz being present as an essential.

The metamorphosed rocks commonly known as granulites are of various composition, and contain little idiomorphic matter; but it is a question if we may employ "granulitic" in any sense not determined by the author of the term. A large number of rocks, both of igneous and metamorphic origin, are built up of granules of similar size and partially rounded outline, as if movement had prevented the growth of well-developed forms during

* For Lévy's nomenclature see "Divers modes de structure des roches éruptives etudiées au microscope," *Ann. des Mines*, sér. 7, t. viii. (1875), p. 337. Also *Structures et Classification des Roches éruptives*, Paris (Baudry), 1889.

† As an eruptive rock of the acid series; *Bull. Soc. géol de France*, 3me. sér., t. ii. (1874), p 180.

consolidation. For this interesting structure, which one is tempted to call "granulitic," we shall here use the somewhat vague term "granular," or **microgranular** when necessary. Commonly, indeed, the microscope is required for its correct appreciation (see fig. 28); but the absence of well-developed forms, such as prisms of felspar or pyroxene, is noticeable with a lens on the surface of the rock itself.

Ophitic Structure.—Often with the eye the crystals of one constituent will be seen to have developed freely, while another constituent has settled down in large crystals round them, so that the interspaces of the former are filled over considerable areas by material having parallel cleavage-surfaces or crystal-faces. On turning the rock-specimen in the hand, the light will glance from some such surface and show the real continuity of areas that appear distinct from one another on the broken surface of the rock. This structure derives its name from its occurrence in the dolerites and gabbros of the Pyrenees, which were called "ophites" by De Palassou. It is, however, extremely common in the dolerites and diabases of all countries. Prof. G. H. Williams (*Journ. of Geol.*, vol. i., p. 176) has used the term "poikilitic" for what seems practically the same structure, applying it particularly to cases where the enclosing or "ophitic" mineral is felspar. The appearance known as "lustre-mottling" arises when the included crystals are small in proportion to the cleavage-surfaces of the surrounding and subsequently-developed mineral. "Lustre-mottling" is common in the Peridotites. (See fig. 39, and Index.)

Pegmatitic or Graphic Structure.—Two constituents, most commonly quartz and felspar, have developed simultaneously in large crystals mutually intergrown. The felspar being predominant, the quartz appears as hook-shaped and irregular forms apparently disconnected from one another. The cleavage-surfaces of the felspar thus give the effect of "lustre-mottling;" but the quartz, when examined microscopically, is found also to be optically continuous over considerable areas of the rock. The structure thus resembles that which would be produced if two sponges were to grow up simultaneously, the one filling all the hollows and ramifying passages left by the mode of growth of the other. Graphic granite provides the best and almost only type. (See fig. 25.)

The same structure when minute is styled **micropegmatitic.** Micropegmatitic intergrowths are often grouped in delicate globular forms around porphyritic crystals of quartz or felspar. These micropegmatitic structures commonly require the micro-

scope for their detection, and have been appropriately styled "micrographic" by Harker, and also "granophyric" by Rosenbusch. The term "granophyre" was, however, used by its inventor, Vogelsang, in a sense that included all microcrystalline igneous rocks.

Orbicular Structure.—A rare structure in which the crystals are grouped so as to form spheroidal aggregates, with or without radial or concentric arrangement. A fine example is the orbicular diorite ("Corsite") of Corsica. This structure may be regarded, with Vogelsang, as the highest development of the spherulitic.

Fluidal Gneissic Structure.—A banded or foliated structure arises in some holocrystalline rocks during their original flow, and may be designated as above, to distinguish it from the metamorphic gneissic structure. Its fluidal origin is clearly proved in those special instances when the planes of foliation run parallel with the bounding walls of the intrusive sheet or vein, and across the structural planes of the surrounding and invaded rock. The smaller constituents flow round "eyes" formed by the larger ones. Sometimes the intrusion of a non-homogeneous magma produces a banded gneissic structure on a handsome scale (see, for instance, Geikie, *Anc. Volcanoes of Great Britain*, vol. ii., figs. 336 and 337). In many other cases, a granitoid rock intrudes in thin sheets along the bedding-planes of a shale, or along the foliation-planes of a schist, and its fluidal gneissic structure is due to the laminæ of foreign matter carried off by it. (See Pl. II., fig. 5.) In such cases, a composite rock results, the alternating layers of which may be strongly contrasted, consisting as they do of absolutely different rock-types. An interchange of minerals occurs on the surfaces of junction; but it is obvious that the general structure is that of the original mass, preserved in spite of much contact alteration.

CHAPTER XII.

SOME PHYSICAL CHARACTERS OF ROCKS.

I. Specific Gravity.—As will be seen when various rock-types are examined in detail, the specific gravity is often a good guide to chemical constitution. The specimen must be selected with the following precautions:—

1. It must be representative of the mass under examination, and sufficiently large to include all the constituents in their correct average proportions.
2. It must be free from flaws and cavities.
3. It must be unweathered, except in certain special investigations.

The general methods of determining specific gravity are detailed upon pp. 22 to 27.

To observe the first precaution, it is often necessary, and, indeed, safer, to use Walker's rather than the refined chemical balance, which will not weigh a specimen of more than 100 grammes. The method devised by Mohr for measuring the displaced water is highly satisfactory in dealing with crystalline rocks of coarse grain and any specimen which it is inadvisable to reduce in size. The displacement-apparatus consists in simple form of an inverted glass bell-jar furnished below with an india-rubber tube and clip and supported on a stand. The water placed in the vessel can be thus run off from below, accuracy being ensured by using the clip rather than a tap, and by letting the tube terminate in a jet formed of glass tubing. A horizontal wooden bar bearing a needle is laid across the top of the vessel, the needle projecting about 3 or 4 cm. downwards. To ensure constancy of position, the points where the bar habitually rests on the glass rim should be marked with a file or by gummed slips of paper.

The vessel is filled with water; the end of the needle is lightly greased, and allowed to project into the liquid. Looking up from below at the bright totally reflecting surface of the water, the clip is released, and the water is allowed to run off until the needle-point just disappears from view. It now exactly touches the upper surface of the water and gives us a standard to which to refer. The specimen, which has been weighed upon a strong but accurate balance, is then lowered by a fine thread or wire

into the vessel, the water rising higher by the addition of its bulk. When all bubbles have disappeared, a graduated measuring-glass is taken, the divisions of which correspond to the units of weight used in the determination of the weight in air. Thus, if grammes were used, the glass will be graduated in cubic centimetres. Into this glass the water is run off until the needle-point, observed from below as before, again exactly touches the surface of the water. The amount run off gives the bulk of water (d) displaced.

$$G = \frac{\text{weight in air}}{d}.$$

To observe the second precaution, some rocks, such as porous sediments or pumiceous lavas, must be reduced to a powder and determined with the specific gravity bottle, the finest dust being sifted or blown off to avoid choking of the small tube in the stopper.

To observe the third precaution, it is often well to pick up clean chips from specimens trimmed in the field, which, selected from a large number, will serve both for the determination of specific gravity and the making of microscopic sections.

Since the range of specific gravity in rocks, the coals being omitted, rarely exceeds the limits 2·2 to 3·4, many very diverse rocks have the same specific gravity, and the results are not of value in absolute determination. But in the case of igneous rocks, provided that specimens are selected and examined from different parts of an exposure, an excellent idea can be formed, from the specific gravity alone, of the silica-percentage of the mass.

II. Fusibility.—Though it is seldom desirable, on account of their complexity, to treat rocks before the blowpipe as if they were simple minerals, yet in a few cases the determination of the fusibility proves of service. The older writers relied, indeed, more upon this character than has since been thought desirable, and the nature of the glasses produced was closely studied. It is obvious that the application of the flame, in the absence of an acid, will decide between a soft rock composed of silicates and a limestone, the former in all probability fusing to a glass while the latter becomes luminous and crumbling. The natural glasses also have various degrees of fusibility, the more highly silicated fusing with greater difficulty than the basic. Thus obsidian fuses at about 5 of von Kobell's scale, and tachylyte as easily as 2·5. Care must be exercised, however, in dealing with these glasses that the splinters used do not present unusually thin edges.

The interesting observations of Berger and of Beudant showed that the treatment of volcanic glass in the flame of a blowpipe occasionally results in the formation of a pumice as fusion gradually takes place. (*Trans. Geol. Soc.*, 1816, p. 191, and *Voyage en Hongrie*, 1822, vol. iii., p. 362.)

The volatile materials thus liberated swell up the whole glass, until in some cases it almost rivals the intumescence of a borax bead. Professor Judd* found that the obsidian granules (Marekanite) of Marekanka, in Siberia, may be converted into a pumice of eight or ten times their original bulk; and similar results are obtainable with the lavas of Krakatoa. The experiment should be repeated, by way of comparison, on any specimen of volcanic glass.

In the case of an igneous rock that has undergone alteration, the fusibility can be of little service, since a very small admixture of hydrous minerals such as zeolites may suffice to considerably increase the fusibility of the mass.

III. Hardness.—This important property, rendering the use of the knife imperative at all times, has been already referred to on p. 93.

CHAPTER XIII.

THE CHEMICAL EXAMINATION OF ROCKS.

A number of ordinary qualitative tests may be applied to rocks, and the examination with acids, hot or cold, is naturally of great value in the detection of carbonates.

Pure dolomites, such as at times occur among crystalline masses, will effervesce only when the acid is heated; but magnesia occurs in many limestones in which the acid test is unavailing. The ordinary dolomitic limestones thus effervesce freely in cold acid, and the magnesia can only be safely determined by precipitation from solution by hydric disodic phosphate in the ordinary way. On the other hand, we must here repeat the warning that a rock which gives no effervescence when touched with strong cold acid may yet belong to the group

* "On Marekanite," *Geol. Mag.*, 1886, p. 243; also, "The Natural History of Lavas," *ibid.*, 1888, p. 6.

commonly styled limestones, being in fact a dolomite; and the resemblance, except in hardness, of some of these rocks to compact grey gypsums or even quartzites makes it necessary to emphasise this caution.

It is constantly of service to examine the compact or glassy groundmass of an igneous rock for potassium, by the method described on p. 85, which has the advantage of giving roughly quantitative results.

The treatment of a rock with acid is frequently important as revealing an insoluble residue, which should always be examined further. The division, however, of every rock into a soluble and insoluble portion, prior to analysis, is now regarded as of little value, and the ordinary plan pursued is to make a thorough fusion of a weighed quantity of the powder with carbonate of potash and carbonate of soda. The powder must be obtained by breaking up little fragments of the rock still further upon an anvil. An enlarged form of the steel mortar used in blowpipe analysis (p 40) will serve well. The material is ground and reground, a portion at a time, in a fair-sized agate mortar until the powder is practically impalpable between the fingers. Too much care cannot be given to this simple preparation of the material used in the analysis, since imperfect fusion may result if the particles are not sufficiently fine, and the silica ultimately separated will contain gritty undecomposed matter. Although the precautions and details of the methods employed must be left to chemical works and to personal practice, it may be of service to remind the reader of the successive operations performed during a simple rock-analysis, such as would suffice for ordinary determinative purposes. Naturally the list of substances that might be looked for and separately estimated in an elaborate analysis of material from the earth's crust is as long as that of the known chemical elements; but the proportions in which the below-mentioned oxides occur are often of fundamental geological importance. Unless, however, such substances as manganese, titanium, barium, &c., are separately determined, the analysis must be regarded as only approximate, and as serving for classificatory purposes rather than for refined discussion. This is clear from the detailed papers by Messrs. Clarke and Hillebrand, which should be in the hands of all who would analyse silicates (*Bull. U.S. Geol. Survey*, No. 176, price 15 c.; also 167 and 168. See also Washington, *Manual of the Chemical Analysis of Rocks*, 1904, Wiley & Sons, New York).

Summary of Determinative Chemical Analysis of a Rock.

1. **Loss on Ignition.**—Dry the powdered rock in an air-bath at 110° C.; transfer about 1 gramme to a platinum crucible, and determine the weight of the quantity thus used. Then ignite strongly over a gas blowpipe, cool in a desiccator, and weigh again. Ignite a second time and weigh, repeating this until the weight is constant. The difference thus found is due to loss on ignition, which generally represents water. Where it is necessary to determine carbon dioxide, a sample of the powder must be decomposed by acid in an apparatus in which either the gas evolved is allowed to escape and is determined by loss, or in which it is collected in an absorption-tube by soda-lime and weighed. (See Hillebrand, *op. cit.*, p. 101.)

2. **Silica.**—Prepare a fusion-mixture by minutely mixing 13 parts by weight of potassium carbonate with 10 parts sodium carbonate. Add to the ignited powder in the crucible, or to a fresh sample if the heating has caused it to fuse or frit together, about four times its weight of fusion-mixture, mixing carefully and very thoroughly with a rod or platinum spatula. Fuse at first over a Bunsen-burner, the lid of the crucible being kept on, and avoiding too great heat at the outset. Then apply the blowpipe until the whole mass runs freely together and ebullition ceases. The flame should be directed obliquely, and should not envelope the whole crucible.

Remove and stand the crucible on a cool surface, such as an iron plate, so that the fused mass may crack away from the wall of the crucible. Place in a porcelain or platinum dish with hydrochloric acid and water, covering quickly with a clock-glass to avoid loss by effervescence of the carbonates. Warm, and allow to stand until decomposition is complete. Evaporate to approximate dryness in a water-bath (*Clarke and Hillebrand*). Moisten again with strong hydrochloric acid, add water, and warm. The silica should now float about lightly in the liquid when stirred, while all the bases are in solution. Filter off the silica; evaporate the filtrate, treat as before, and add the small quantity of silica thus obtained to that already in the filter. Ignite for about twenty minutes, and weigh. If gritty matter occurs amid the silica, the fusion has not been satisfactory, and the process must be begun again.

3. **Alumina and Ferric Oxide.**—Add to the filtrate a few drops of nitric acid, in order to ensure the conversion of ferrous to ferric salts. Then add ammonium chloride, and ammonia in

very slight excess, and boil. Filter off the precipitate of alumina and ferric oxide, obtaining the filtrate *a*. When thoroughly washed, re-dissolve the precipitate into another vessel, and divide the subsidiary filtrate thus obtained into two measured quantities. Thus it may be made up to half a litre by dilution in a marked flask, and 250 cc. may be drawn off with a pipette. In this portion precipitate alumina and ferric oxide as before; filter, ignite, and weigh. Draw off 100 cc. from the portion remaining in the flask, and determine the iron in this volumetrically by means of bichromate or permanganate of potash. Make a check-determination by drawing off another 50 or 100 cc. Divide the weight of iron found by ·7, which will give the weight of ferric oxide. Deduct this from the joint oxides, the alumina being thus found by difference. Ferrous and ferric oxides must be separately determined in all exact analyses. (See especially Hillebrand, *op. cit.*, p. 88.)

4. **Lime.**—To the original filtrate *a*, which must contain ammonia in excess, add excess of ammonium oxalate. Allow to stand for 12 hours. Filter, and ignite strongly; weigh, and repeat till the weight is constant. The precipitate is thus converted into lime.

5. **Magnesia.**—Ammonia being in excess, add hydric disodic phosphate to the filtrate, stirring very carefully with a rod, since the precipitate clings to any parts of the beaker that may have been in the least degree abraded by touching. Stand for 12 hours and filter cold. Wash the precipitate with a mixture of 1 part ammonia and 3 water, and ignite, the filter being burnt separately in the lid of the crucible. Where a large quantity of magnesia is expected, a porcelain crucible should be used, to avoid injury to the platinum. The ignited precipitate is the pyrophosphate ($Mg_2 P_2 O_7$). To estimate as magnesia, multiply by ·36036.

6. **Potash and Soda.**—These alkalies are best determined by the Lawrence-Smith method. Mix intimately 1 part of the powdered rock (about half a gramme) with one part of ammonium chloride and 8 parts of pure calcium carbonate. Heat for about an hour in a deep platinum crucible, which is best supported almost horizontally over a flat-sided Bunsen-flame, and under a conical iron shield. The flame must be applied very gradually at first to avoid rapid volatilisation of the ammonium chloride, and the temperature should at no time rise above dull redness. The decomposition is effected without complete fusion. Dissolve out the fritted mass in water in a dish and filter. The filtrate contains the metals of the alkalies in the form of chlorides, with some portion of the materials used in decomposition.

Precipitate the lime from the filtrate by ammonium carbonate; filter and evaporate down, testing the filtrate as it becomes more concentrated with a drop or two of ammonium carbonate solution. If lime is still present, precipitate it and filter again.

Evaporate to dryness in a small dish, and gently drive off by further heating the ammonium chloride and ammonium carbonate. A dark stain may appear, which is due to impurities in the ammonium carbonate, and may be neglected. Excessive heat must be avoided, lest a portion of the chlorides of the alkali-metals should be lost. Weigh the joint chlorides in the dish while the latter is still slightly warm.

Dissolve up in water, add platinic chloride, and evaporate almost to dryness on a water-bath. Add alcohol, and allow to stand for some hours, the precipitate of potassium platinic chloride being insoluble in alcohol. Filter on to a weighed filter, wash with alcohol, and dry at 100°. Weigh with the filter without ignition.

To calculate this precipitate as potash, multiply by ·19272. Divide this result by ·63173, which gives the weight of the potassium chloride in the joint chlorides. Deduct this from the joint weight and multiply the remainder by ·53022. This gives the weight of soda.

CHAPTER XIV.

THE ISOLATION OF THE CONSTITUENTS OF ROCKS.

In the case of a coarse-grained rock, clearly composed of heterogeneous materials, it is not difficult to break out with the hammer or the pliers fragments or crystals of individual constituents, which can then be submitted to special tests. It is, however, highly desirable that a microscopic section should have been previously prepared, in order that the purity of the crystals which are to be examined, and their freedom from enclosures, may be satisfactorily ascertained. This precaution is especially necessary when chemical or microchemical tests are about to be applied. Where the selected grains are small and translucent, examination of them when mounted in water under the microscope will often assure the observer of their purity or the reverse.

Many sedimentary rocks, such as sandstones, can be broken up with the pliers or even with the fingers, and the grains spread out on paper for identification. Other rocks, such as clays, may be broken up after prolonged treatment in water, the materials of varying fineness being successively washed off into separate vessels, and an often valuable residue of larger grains, small fossils, &c., being finally left behind (see p. 198).

When a rock is, however, compact and coherent, its constituents can be isolated only with difficulty; and at the beginning of the present century a large number of masses were classed as homogeneous, or even as mineral species, which were in reality fine-grained rocks in which it seemed impossible to determine the constituents. To the French geologist Cordier we owe a series of researches that shed a vast amount of light on the constitution of the igneous varieties of such rocks. Since the task he set himself was so eminently one of mineral-isolation, a summary of his work may be given appropriately here, before we discuss the modern methods by which such investigations have been facilitated. For if modern petrology appears to owe little to the men of 1800, it is not because these early researches were less accurate or in any way less laborious than our own, but because they were for a time forgotten by geologists amid the excitement of palæontological discovery.

In the autumn of 1815, P. Louis Cordier read to the Academy of Sciences at Paris his *Mémoire sur les substances minérales dites en masse, qui entrent dans la composition des Roches Volcaniques*

*de tous les âges.** Struck with the probability that the compact or more glassy matrix of volcanic rocks consisted of determinable mineral substances, he put before himself the following question:—"Are the undetermined volcanic groundmasses mechanically constituted, and, in the event of it being possible to determine their mechanical constitution, what are the mineralogical units that compose them?"

After many unsatisfactory experiments, Cordier had recourse to two modes of discrimination, the microscope and blowpipe-examination after the method practised by de Saussure.† He considered it probable that the particles produced on the breaking up of his volcanic groundmasses would belong to the common crystallised minerals that occurred in coarser specimens of such rocks. Hence he began by reducing well-known minerals to powder by pressure under a pestle, until he obtained samples in which the grains were from ·05 to ·01 millimetre in diameter. He then examined these under a microscope magnifying 13 or 20 diameters, rotating the object-carrier so as to view each grain in several positions with regard to the light falling on it. The clearness of the characters displayed by the various minerals came to him as a welcome surprise.

He examined in this way pyroxene, felspar, olivine, titanic iron (much magnetite was probably included by him under this term), amphibole, mica, leucite, and hæmatite. He also tested the hardness of the grains, and their fusibility on de Saussure's kyanite splinter, and observed on the same support the action of one mineral upon another, placing the two grains under examination in contact with one another and fusing them in the same flame.

In his comparisons of these types with the constituent granules of the groundmasses, he felt that local variations must be eliminated; hence he was careful to employ, as far as possible, the larger and identifiable crystals of a rock as guides in the determination of the particles of its matrix. We now know that such porphyritic crystals are apt to differ very widely from those of the "second consolidation;" but even this precaution of Cordier is an illustration of the general refinement of his work.

Under the head of volcanic rocks he included the products of active volcanos, of denuded cones, and of ancient centres which had been covered by marine deposits of the remotest age. He powdered up these rocks, microcrystalline or glassy, washed the

* *Journal de Physique*, t. lxxxiii. (1816), pp. 135, 285, and 352. Abstract by A. Brongniart in same journal, t. lxxxii., p. 261.

† See p. 46 of this volume.

particles so as to procure samples of suitable fineness, and submitted them to the same tests as his typical mineral series. He extracted the opaque black granules with a bar magnet,* and referred them to his "fer titané," which contained only a very small proportion of titanium, and which corresponds in these rocks to our magnetite and titaniferous iron oxide. Finding a small portion of the opaque grains not thus attracted by the magnet, he compared them first with chromite and melanite, and finally classed them as ilmenite. His preliminary assumptions were now fully justified, and he distinguished as the constituents of his "pâtes lithoïdes" the minerals felspar, pyroxene, amphibole, mica, "fer titané," leucite, olivine, and hæmatite. He also put an end to the idea that amphibole rather than pyroxene was the dominant black silicate in basalt and in the allied darkly coloured rocks. He finally divided his lithoidal lavas into "leucostines," in which felspar predominated, and "basalts," which fused to a black glass and in which pyroxene was abundant.

Cordier then compared in detail the granular and often schistose rocks known as petrosilex, cornéenne, and trap, with his ancient and modern lavas, and concluded that the two groups had nothing in common, beyond a few familiar crystallised minerals. In the former group he notes as distinctive constituents quartz, diallage, talc, chlorite, magnetite, iron pyrites, and pyrrhotine.

He next turned his attention to volcanic scoriæ, and proved their composite character with similar success, showing that the microscopic crystals in them were often embedded in a glassy matrix. His researches on truly vitreous lavas ought similarly to have gone far towards a rational treatment of such rocks; many glasses, however, have been regarded as minerals rather than mineral aggregates from the middle ages to the present day. Cordier traces admirably the passage from the compactest basalt to the black glass (tachylyte) for which he reserves the old name of "gallinace." The more felspathic glasses that fused to a white or lightly coloured product he classes in distinction as obsidian.

After an elaborate examination of the altered matrix (wacke) of many tuffs and amygdaloidal lavas, he sums up practically as follows:—

That the mineral substances styled massive, forming the

* Fleuriau de Bellevue also used the magnet, and may have determined his minerals partly with the microscope. "Mémoire sur les cristaux microscopiques." *Journ. de Physique*, t. li. (1800), p. 442.

groundmass of volcanic rocks, are, with the rarest exceptions, composite in character.

That their constituents are microscopic crystals and glass.

That the crystals belong to the common species above given.

That the vitreous groundmasses probably contain material the further development of which would have produced the lithoidal types.

That in many altered volcanic rocks the materials are held together by foreign matter interposed in very minute particles.

That the sixteen types of rock which he establishes are connected one with another by a sufficiently complete series of intermediate types.

That the volcanic rocks have no analogy with those called petrosilex and trap.

That the differences alleged to exist between ancient and modern lavas are entirely superficial, and consist only in minute modifications of texture; vacuoles are thus always present between the constituents of modern lavas, while in the older examples they have become rare or completely absent through infiltration.

Although Cordier probably exaggerated the points of difference between some truly igneous "traps" and his volcanic series, yet his general conclusions were in the highest degree philosophic; and it is indeed pleasant to refer to his classic memoir as an example of what may be done in determinative geology by the union of scientific method with the simplest means. (See also p. 132.)

The **crushing** of crystalline rocks, with a view to the microscopic examination or isolation of their constituents, may be performed between folds of smooth cloth or even paper, to avoid the introduction of extraneous metallic or mineral material; but a hard steel anvil and hammer generally suffice.

The powder of the rock, which must be fairly coarse, is passed through sieves of various mesh, until a sample is procured, as coarse as possible, in which each grain consists of only one mineral species. For this purpose the sieves used in chemical laboratories are convenient, several fitting one above the other; the crushed mineral is placed in the topmost, which has the widest mesh, and, the whole being shaken, each sieve selects a sample increasing in fineness till we reach the lowest pan.

The objection to the use of sieves lies in the fact that some of the constituents may be much more friable than others, and hence for quantitative purposes no one sample may be satisfactory. The contents of each sieve must be examined in order to determine if any mineral has become eliminated from this cause.

The sample, when selected after examination with the lens, may be picked over by the aid of that instrument, or upon the stage of a microscope with a low power. A fine brush should be moistened with water (Dr. Sorby recommends glycerine) and brought in contact with the grain to be picked out. It is then dipped just below the surface of distilled water in a watch-glass, and the grain is at once detached and sinks.

In this way, by care and patience, a quantity of any one constituent can be accumulated, sufficient even for a chemical analysis. But for merely qualitative tests a very few grains will be sufficient, and excellent material can be quickly obtained to which microchemical reagents may be applied.

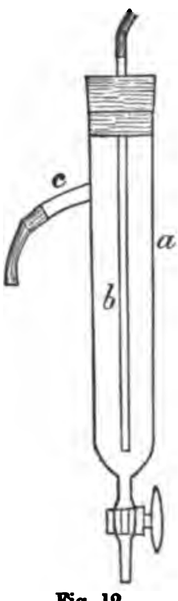

Fig. 12.

The removal of light material, such as clay, fine dust, &c., from heavier or coarser constituents may be performed by washing, as in an apparatus described by M. Thoulet * (fig. 12). A large tube, *a*, terminating in a tap below, is fitted with a rubber cork through which a finer tube, *b*, passes. A tube, *c*, opens through the side of *a*. The powdered material is placed in *a* and water is introduced through *b*. This rises in *a* and flows over at *c*, carrying with it, if the operation is sufficiently prolonged, all the light substances thus washed out of the material.

In separating minerals of different specific gravities, water is introduced at *c* and flows out up *b* when *a* has become full. This current keeps the powder well disturbed, and by regulating it none of the material escapes up *b*. Check the flow gradually, and the grains of different characters will descend successively, forming distinct layers at the bottom. These can be drawn off by the tap, and a fairly pure amount of any particular constituent can be collected. Plate-like minerals, such as mica, will probably appear among the upper layers. It is clear that simple forms of such an apparatus can be constructed with glass tubes, corks, rubber tubing, and a clip to act as a stop-cock.

Prof. Derby, in 1891, showed how an ordinary miner's pan will suffice to separate a good quantity of the heavier minerals from a powdered rock. Dr. G. P. Grimsley ("Granites of Cecil

* "Séparation mécanique." *Bull. Soc. Min. de France* t. ii. (1879), p. 22.

Co., Md.," *Journ. Cincinnati Soc. Nat. Hist.*, 1894) used a pan 12 inches in diameter for his work on granite soils. The powder is well stirred with water, and the earthy portion poured off; the granular residue is stirred with more water, "by a combination of a spherical and elliptical movement of the pan." Then, by a quick side-movement, the water is thrown off, carrying the lighter minerals and the floating mica. Repeat until only a small residue is left, which contains the heavy minerals.

The various methods of decantation and separation by washing in moving water, which have been adopted for the mechanical analysis of soils, are well discussed by Wiley (*Principles of Agric. Analysis*, vol. i., 1894, pp. 171-247). Simple but systematic methods of decantation in ordinary beakers appear to be as reliable quantitatively as far more elaborate methods.

Cordier extracted some constituents by the use of the **magnet** (p. 112) after washing. Composite grains, containing only minute particles of magnetite, may be taken up, but can be picked out if the iron oxide itself is required to be pure. It is useful to cover the end of the magnet with a sliding cap of tissue-paper. This is kept in contact with the end while passing over the powdered rock, and the magnetic particles adhere to it. On withdrawing the magnet to the collecting-vessel, the cap is thrust forward and the material falls off into the vessel.

M. Fouqué * uses an electro-magnet, connected, if necessary, with six Bunsen-cells. By graduating the strength of the current, the constituents of a rock can be fairly sorted; first the magnetite, then the pyroxene, the olivine, and the felspars and allied minerals which contain traces of magnetic substances. A residue of felspars and "felspathoids" remains. The glassy matrix of igneous rocks is the most common source of error; if it is pyroxenic, it may, by inclusion in the felspar, cause the removal of a large quantity of the latter, leaving only the purer quality; but in many cases it is highly silicated and scarcely ferriferous, and cannot be separated from the felspars that are to be tested by Szabó's or other reactions. Microscopic examination, then, must decide on the suitability of such selected material for refined determinative tests.

In practice with Fouqué's method, the ends of the electro-magnet may be covered with thin paper, to prevent the adhesion of non-magnetic particles to any moisture on the surface of the iron. The powder is placed on a large card and jerked about close under the poles. When a certain amount of material has

* "Nouveaux procédés d'analyse médiate des roches." *Mémoires présentés par divers savants à l'Acad. des Sciences*, t. xxxii., No. 11. See also *Minéralogie Micrographique.*

been attracted, the card is withdrawn and a clean card or paper substituted; the current is then interrupted, and the particles fall off and are collected.

M. Fouqué has separated by this process microscopic prisms of felspar, the presence of which was not revealed in the rock even when a strong lens was used; but a small quantity of glassy matrix always remained associated with them. In this case the experiment was made upon an impalpable powder.*

The possession of the **heavy liquids** described on pp. 29 to 31, the earliest of which was introduced by Sonstadt for the determination of specific gravities and the separation of gems from sand, has given to geologists a most valuable method for the isolation of the constituents of rocks. It is clear that if we prepare a solution of density intermediate between the densities of any two constituents, one of these will float up to the surface while the other will sink. If the lighter mineral is the only one to be collected and examined, the operation may be performed in an ordinary beaker and the surface-material skimmed off with a spatula. For economy of the liquid, the beaker should be fairly narrow, since some depth of liquid must be used to allow of perfect separation. If Klein's convenient borotungstate of cadmium solution is used, the powdered rock must be treated beforehand with dilute acid to ensure the removal of carbonates.

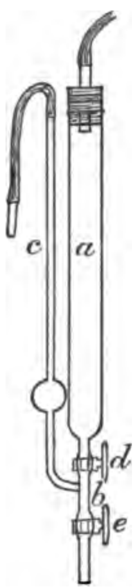

Fig. 13.

The material must be well stirred on immersion, and both top and bottom layers stirred later to prevent entangling of inappropriate constituents in either. The particles when removed must be well washed with distilled water, or with benzene if methylene iodide is used in the separation; the washings are collected in a dish and evaporated down until a concentrated liquid is again obtained for future use.

The material separated, when washed and dried, should be carefully searched over with a lens or low microscopic power, since some composite grains are sure to be included. Any doubtful object must be rejected if a quantitative analysis is contemplated; or, for ordinary qualitative tests, only the purest grains must be selected.

* M. Fouqué also notes that, contrary to expectation, chlorite is not picked out by the electro-magnet.

But in the majority of cases more delicate means of separation will be required, and one of the neatest methods has been devised by M. Thoulet* (fig. 13). A glass tube, *a*, 15 mm. in diameter and about 30 cm. long, is graduated in cubic centimetres. At its base it is prolonged by a narrower tube, *b*, in which are two taps. Between the taps a tube, *c*, enters, bearing above a rubber prolongation, which is closed at will by a piece of glass rod thrust into the end. The tube, *a*, can be closed by a rubber cork through which a tube passes which may be connected with an air-pump.†

To perform a separation, a quantity of the dense liquid is poured into *a*. The powdered rock is added, the air-pump is applied so that the particles may be freed from bubbles, and the minerals of greater specific gravity than the liquid will fall to the bottom.

These are drawn off through the two taps. After each drawing off of the heavier particles, the tap *d* is closed, and the liquid that has run out is drawn up once or twice into *b* by sucking some of the air out through *c*. In this way the last particles are washed down out of *b* into the receiving vessel. A fine tube bent upwards at the end, through which water is allowed to run, also serves to wash out *b*; but the liquid becomes thus further diluted and requires a longer process of concentration before it can again be used.

e is then also closed; and water can be added from above until the liquid is sufficiently diluted for a fresh mineral to descend. To procure a solution of particular density, the amount in the tube *a* is read off, and water is added according to the following formula:—

$$\left.\begin{matrix}\text{Volume of}\\ \text{water added}\end{matrix}\right\} = \frac{\text{Vol. of liquid} \times (\text{Density of liquid} - \text{Density of required mixture})}{\text{Density of liquid} - 1}$$

The two liquids are mingled by opening the tap *d* and blowing lightly through *c*.

For ordinary purposes simpler apparatus works extremely well. Thus Herr T. Harada, about 1881, used what is practically an ordinary separating-funnel of the shape of a pear rather than a globe. The stopper at the top and the tap below permit of the thorough mixing of the liquid and the powder by agitation,

* "Séparation mécanique des divers éléments minéralogiques des roches." *Bull. Soc. Min. de France*, t. ii. (1879), p. 17. The apparatus is sold by Dagincourt, 15 Rue de Tournon, Paris, for 35 francs.

† It must be remembered that rubber tubes and stoppers should not be used with liquids that require to be diluted with benzene.

though care must be taken lest particles remain clinging to the sides of the vessel above the surface of the liquid. The objection to the use of taps is, however, obvious, and becomes more and more forced on one in practice. It is difficult, moreover, to get a tap of sufficiently large bore unless the instrument has been specially made. The tap of Harada's apparatus may be got rid of by substituting a piece of rubber tubing and a spring-clip, such as are often used with burettes. The portion below the tap or clip must be carefully washed out, to prevent the accumulation there of crystallised products from Klein's solution, which will check free action when the liquid above has to be drawn off.

The power of closing the vessel by a stopper above is useful in preventing the too rapid flow of the solution, since the outfall of the heavy particles on the opening of the lower orifice can only occur as air rises through the liquid into the upper part of the vessel. But very many useful separations can be performed in the simplest possible manner in an ordinary open chemical funnel about 8 cm. across. A rubber tube and clip are fixed at the outlet of the funnel, and, in place of shaking, the powder and the liquid are mixed by stirring with a rod. The clinging of particles to the sides of the funnel and glass tube causes occasional errors, and all such sluggishly ascending or descending grains must be touched and kept moving with the glass rod. The rubber tube must be removed and thoroughly cleaned before putting the instrument away; a bent tube, like that used with Thoulet's apparatus, serves well to wash out the part below the clip during each successive separation.

Dr. J. W. Evans (*Geol. Mag.*, 1891, p. 67) has found the following a safe and thorough method of removing the heavy minerals without drawing off any of the upper material :—Take a thistle-headed funnel or pipette, the tube of which is fairly long and will fit into that of the separating funnel from above. Surround the end of this with a piece of rubber tubing, so that it can be thrust down into the upper part of the neck of the separating-funnel and will there act as a stopper. When the separation has taken place in the liquid, and the heavier minerals are all resting in the tube of the separating funnel, just above the clip, insert this stopper, which should be closed during its descent by a piece of glass rod thrust down into it from above. Then remove the rod, open the clip, and the heavier materials will come out as usual, but without any necessity for precaution in their release. Pour distilled water down the tube of the stopper, and the tube of the separating-funnel will be thus efficiently

washed out. Close the clip, remove the stopper, and a second separation can be made by further dilution of the liquid.*

Mr. W. F. Smeeth,† however, successfully dispensed with both clips and taps. He uses an urn-shaped vessel with sloping sides, closed above by a large stopper and open below, the contracted base being ground so as to fit into a tubular bottle, which has an expanded lip and which acts as a support. An extra glass-stopper with a long handle is made so that it can be passed through the upper opening of the urn and thrust down so as to close the passage into the bottle. The dense liquid and the powder are shaken together in the instrument, the ordinary stopper being in its place and the urn and bottle remaining connected. The heavier particles will thus descend into the bottle. Now pass in the long stopper, moving it in the liquid as it descends so as to free it from any adhering particles of the lighter material; close the base of the urn with it and lift off the urn from the bottle. The two classes of materials are thus efficiently separated from one another. If the urn is now fitted into a second and similar bottle, a further separation can be proceeded with by removing the long stopper and diluting the liquid to the requisite amount. Mr. Smeeth informs us that the instruments were made for him by Messrs. Becker, of London. He suggests as the simplest type of this apparatus an ordinary funnel cut down so as to leave a stem half-an-inch in length. This is connected by a piece of rubber tubing with a glass tube which serves as the receiving bottle. The materials are mixed with the liquid in the funnel; its lower orifice is closed by a glass rod carrying an india-rubber cork at the end; and the rubber tubing can then be pulled away safely from the shortened neck of the funnel, the two parts becoming thus disconnected.

Herr A. Hauenschild has recently invented a very compact and efficient apparatus, consisting of a large glass tap, with two lateral notches instead of a central opening, whereby the passage of particles is facilitated. Each end of the short wide tube in which this tap is placed is ground, and over each a tubular vessel with a foot is fitted. The upper and lower ends of the instrument are thus identical, except that one is inverted, its foot remaining upwards. The liquid and powder are placed in

* Mr. H. Hartley has described a neat instrument of this type, which avoids the use of rubber (*Min. Mag.*, vol. xiv., 1905, p. 69). It is made by Messrs. Müller, Orme & Co., London.

† *Scientific Proceedings of the Royal Dublin Society*, vol. vi. (new series; 1888), p. 58. Sollas, *Trans. R. Irish Acad.*, vol. xxix., p. 430.

the lower vessel, into which the central tube, containing the closed tap and supporting the upper inverted vessel, is now fitted; the instrument is then inverted, and, in due course, the heavier particles can be drawn off into the second vessel, which is now below. Hauenschild's separation-apparatus is sold by Muencke, 58 Luisenstrasse, Berlin, for 12 marks.

Prof. Sollas (*Nature*, vol. xlix., p. 211) has shown how particles may be removed from any zone of his diffusion-column (see p. 31), by inserting a pipette of 1·5 mm. bore, plugged at its base by a stem of Esparto grass, round the end of which a little unravelled cotton thread is wound. This stem is inserted from above; the pipette is thrust down until its end lies against the grains to be extracted; the plug is then pulled back slowly, and the fluid and grains follow it into the tube. A very thin glass rod, bent up at one end into a crook, is then thrust down parallel to the pipette, and the crook is pulled up so as to enter and plug the bottom of the pipette. Now remove both together, clean off foreign grains from the outside of the pipette with blotting-paper, and wash out the collected and isolated grains.

Where a liquid of high density is required, Dr. J. W. Retgers has recommended the use of certain easily fusible salts, on which he has made a careful series of experiments. In 1893 (*Neues Jahrb. für Min.*, 1893, Bd. i., p. 90) he introduced thallium silver nitrate, which melts at 75° C., giving a density of nearly 5·0. It can thus be manipulated on a water-bath, and can be diluted by water, added carefully drop by drop. Sulphides, however, are attacked by it. The joint thallium nitrate and acetate, melting at 65° C., with G. = 4·5, gave also good results (*Neues Jahrb.*, 1896, Bd. i., p. 212). In a later paper (*Ibid.*, 1896, Bd. ii., p. 183), Retgers recommends mercurous nitrate as cheap, melting at 70° C., with G. = 4·3. Quickness is necessary during a separation, as some decomposition of the salt occurs. The most satisfactory salt is now reported to be thallium mercurous nitrate, melting at 76° C., with G. = 5·3. This can be diluted with water, and has no effect on sulphides.

The procedure is to effect the separation in the melted salt in a test-tube, with a fair depth of liquid. When the heaviest minerals have sunk, remove from the water-bath, and dip the outside of the test-tube into a glass of water, moving it about, so as to cool it quickly. This prevents the minerals from floating up again during the rise of density on cooling. Then break out the bottom of the tube, remove the glass-fragments, and melt off the lower layers into a beaker by means of an obliquely

directed flame. The separated heavy minerals can now be cleaned by washing.

Messrs. Penfield and Kreider (*Amer. J. Sci.*, vol. xlviii., 1894, p. 143, and vol. l., 1895, p. 446) describe improved apparatus for conveniently effecting the separation.

Another, but more risky, method of isolating particular minerals from the powdered rock consists in the use of acids. It is easy thus to extract the silicates from cipollino or calciphyre by dissolving the surrounding carbonates with dilute acetic acid; but stronger acids are likely to destroy some of the minerals that are to be ultimately examined. It is obvious that the nature and strength of the solvent used in each instance must be left to the judgment of the observer.

M. Fouqué* employed hydrofluoric acid in the isolation of the minerals of the lavas of Santorin. He placed about 30 grammes of the rock-powder, from which the finest and the coarsest particles had been sifted off, in a platinum dish into which concentrated hydrofluoric acid had been poured. The materials were inserted cautiously and stirred together; the process of decomposition was arrested at any required stage by pouring in water and washing off thus the fluosilicates, fluorides, and gelatinous products that had been formed. The materials, when washed, should be rubbed with the finger under water to free them from the last traces of the jelly.

In this way the amorphous glassy matrix may be removed from around many minerals, though it may be difficult to free felspars completely from it without seriously attacking the crystals. The ferro-magnesian minerals are attacked only after long immersion; hence they can be isolated from quartz and felspar with comparative ease. The acid is thus found to attack first the glassy matter, then the felspars, then quartz, and lastly the ferro-magnesian group (pyroxene, amphibole, olivine) and magnetite.

The determination of the proportions in which particular minerals are present in a rock can of course be effected by weighing the original powdered material and the successive groups of isolated constituents. Delesse † long ago employed a rougher method, which is simple and very reasonably accurate. It is thus of especial value to observers far removed from refined apparatus. Delesse chose a plane or even polished surface of the

* Fouqué and Lévy, *Minéralogie Micrographique*, p. 116.

† "Procédé mécanique pour déterminer la composition des roches." *Annales des Mines*, 4me. sér. tome xiii. (1848), p. 379. Published also with trifling variations at Besançon, 4to.

rock, or in special investigations the six surfaces of a parallelopipedon cut from it. He covered each such surface with a sheet of goldbeater's skin or fine paper, increasing the transparency if necessary by soaking the covering and the face of the rock in oil. The covering was affixed with gum.

The outlines of the minerals were then traced through with a pencil or fine pen, and the various minerals were coloured with different tints. The tracing was removed from the rock and gummed to a sheet of lead or tin-foil. The outlines were cut round with a pair of scissors and the pieces of the same tint were sorted together. To avoid errors due to irregular thickness of the gum and paper, each sorted group was treated in water and the fragments of the foil were alone finally used.

These groups of fragments were then weighed and compared with the total weight of foil that corresponded to the area or areas of the rock selected, the proportions of each mineral being thus ascertained. Delesse found it convenient to estimate fine lamellar minerals, such as mica, by difference.

When a good balance is at hand, the paper may probably be cut out and estimated directly, without transference to the foil. The modern method has been to employ a thin section of the rock under the microscope, to draw the field seen with a camera-lucida or neutral tint reflector, and to weigh the various parts of the dissected drawing upon a chemical balance.

One of the most interesting results of such investigations is that mentioned by Delesse, who found that minerals of a striking or rich colour are present in much less proportions than the appearance of the rocks containing them seems to indicate.

CHAPTER XV.

THE PETROLOGICAL MICROSCOPE AND MICROSCOPIC PREPARATIONS.

THE microscope may be regarded as the one expensive piece of apparatus in the otherwise modest equipment of the geologist; but a good instrument will obviously last a lifetime. While the details of the stand required have been made the special care of certain well-known makers, it is possible to procure first-class objectives second-hand, and to fit them as one's needs extend.

The essential points of the microscope used by geologists are as follows:—

(1) A good polariser and analyser, both so fitted as to be almost instantaneously brought into position or again removed; the analyser may be above or below the eye-piece, the former, or "eye-piece analyser," being most suited for observations with the quarter-undulation plate or the quartz wedge when crystals are studied in convergent light. The outer flange of the polariser, and of the analyser if this also rotates, must be graduated at every 90°, so that the position of "crossed nicols" can be easily found. In this position, when the shorter diagonals of the calcite prisms constituting the nicols are at right angles to one another, the field of the microscope should be dark until some crystalline substance is placed above the polariser.

(2) Either the stage of the microscope must rotate, or the two nicols must be arranged so as to rotate together, as in the remarkable instrument now made by Messrs. Swift & Son, at the suggestion of Mr. Allan Dick. In either case, the orientation of any crystal in a section with regard to the diagonals of the nicols must be ascertainable by means of a graduated circle and an index. If the stage rotates, as in most instruments, its edge is marked off in degrees (fig. 14).

(3) There must be cross-wires or "spider-lines" in the eye-piece, and a pin must project from the eye-piece and fit into a slot in the main tube, so as to prevent any rotation of the wires, which are parallel to the diagonals of the crossed nicols.

In addition, an easily removable achromatic condenser should be fitted in the aperture of the stage above the polariser, so as to converge the light upon any crystal brought into the

Fig. 14.—Petrological microscope with rotating stage.

centre of the field.* Some means of focussing it within a short range should be supplied, and it is a great convenience when working with high powers if it can be retained as an ordinary condenser whether the polariser is in use or not. If the figures viewed in convergent polarised light are to be seen with the eye-piece, a lens of suitable focus is inserted when required into a slot above the objective.

A quartz wedge, the longer direction of which is parallel to the vertical axis of the crystal from which it was cut, is a very useful accessory. Such wedges are sold for about 20s., and should show, when placed between crossed nicols, a regular gradation of colours from the grey of the first order of Newton's scale at the thin end up to the pink and green fourth-order colours at the thick end. These colours should not, as in wedges of too steep an angle, be crowded together towards the thinner end.

In other points the geologist's microscope resembles the ordinary instrument. **A nose-piece** carrying two or three objectives is invaluable. Owing to the limits imposed by the thickness of rock-sections, very high powers are out of place. If only two objectives are at first purchased, there is little doubt that they should be those styled 2-inch and $\frac{1}{4}$-inch. If a series is available, the following are recommended :—2-inch, 1, $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{8}$ or $\frac{1}{10}$-inch. The rack used in focussing should be long enough to allow of the use of a 3-inch objective, which is occasionally required, particularly when a slide illustrating rock-structure has to be studied. The higher powers are necessary for the study of the groundmass of rocks and for use with convergent polarised light.

If a rotating stage is used, some form of centring is desirable. The adjustment may be made by two screws in the collar into which the objective fits, or similarly by an arrangement beneath the stage itself. In all cases it is necessary that an object viewed with an $\frac{1}{8}$-inch objective should remain in the field throughout a rotation of the stage, and should, if placed on the intersection of the cross-wires, barely deviate from that position.

The difficulties arising from this petrological requirement have been met by microscopists in two brilliant and different manners. Nachet of Paris divides the main tube of the instrument in two, supplies a double arrangement for focussing, and carries the objective with its adjustment on a pillar attached to the rotating stage. Thus the centre of the objective is always in precisely the same relation to any object in the field, since it rotates with the slide itself. This system has also been successfully adopted by Messrs. Crouch & Co., of London.

* A $\frac{1}{4}$-inch objective, supported inverted under the slide and above the polariser, serves to produce the characteristic figures.

In 1889 Mr. Allan Dick* brought forward the instrument already referred to (fig. 15), the details of which were worked

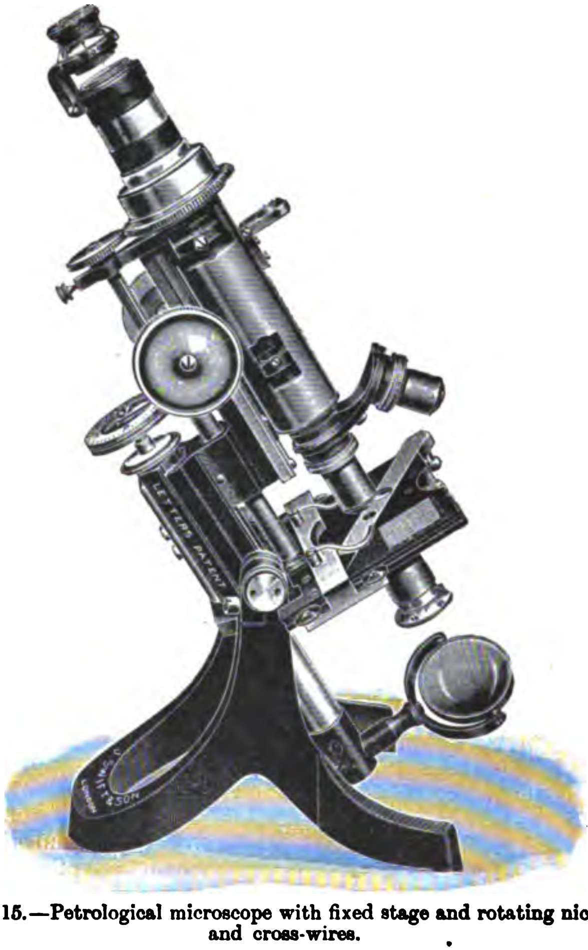

Fig. 15.—Petrological microscope with fixed stage and rotating nicols and cross-wires.

out by Messrs. Swift & Son, of London. The stage is fixed and

* "A new form of microscope." *Mineralogical Magazine*, vol. viii., p. 160. A complete description by Mr. Dick is also published by Messrs. Swift & Son.

of an ordinary compact size; while the eye-piece with its cross-wires, and bearing the analyser above it, is connected by toothed wheels and a rod with the polariser below the stage. With the finger touching one of these toothed wheels, the observer causes the nicols and cross-wires to rotate together, and the vibration-directions of the nicols are thus brought parallel to particular directions in the crystal under examination, an arrangement that renders unnecessary the rotation of the crystal itself. The necessity for adjusting any particular power, however high, until it is exactly centred is thus entirely done away with.

The converging lens slides in and out in a groove cut in the stage; and a number of other ingenious details make this petrological microscope the most remarkable that has appeared since that of Nachet, and certainly the compactest and most convenient of any at present in the field. It is adapted, however, to higher requirements than those of most geological students, for whom the various types of strong instruments with well centred stages provide all that is necessary in ordinary work.

It is often useful to examine small crystals or grains by reflected light under a power of 1-inch or $1\frac{1}{2}$-inch focus. For this purpose the little support suggested by Mr. T. H. Holland * serves admirably and is easily made. A hemisphere is cut out of cork, about $\frac{7}{8}$ inch in diameter, and a small hollow is sunk in the centre of the flat side. The object to be examined is fixed in this hollow by a little wax so that it occupies the exact centre. If the hemispherical surface is allowed to rest in the circular aperture of the stage of the microscope, the support may be turned about in all directions without the object passing out of view or out of focus. Mr. Holland suggests a further use for this support. By turning out a conical hole completely through the hemisphere, widening below, "this simple contrivance may be employed in transmitted light, for adjusting sections of crystals which are supposed to have been cut in any particular direction; but which, as is almost always the case, only approximate what they are represented to be. Suppose, for example, a section of a doubly refracting uniaxial crystal is required, normal to the optic axis. Then by employing the hemisphere, the section can be so adjusted that its optic axis is exactly parallel to the line of collimation of the instrument."

Small objects such as sand-grains may be examined dry upon a glass slip, or by transmitted light when mounted in water under a cover-glass. Should it be desirable to preserve the

* *Science Gossip*, No. 291 (March, 1889), p. 53.

specimens, objects for reflected light should be mounted as follows:—A slip of cedar-wood or mahogany, of the same size as the ordinary microscopic slide, and slightly thicker than the objects to be examined, has a circular hole bored through its centre. It is then backed by a thin piece of card blackened on the side that shows through the aperture. The objects may be fixed by minute drops of gum to this dull black ground in any suitable position. Care must be taken to prevent the gum from rising on to the sides of the objects and imparting to them an artificial appearance of polish. Tiny supports of blotting-paper soaked in gum can be folded into any shape when moist, and will prop up a minute specimen in any required position.

For use with transmitted light, the objects are mounted in Canada balsam, which has a refractive index sufficiently high to prevent the dark-bordered effect and imperfect transparency noticeable when air or even water surrounds the specimens. With delicate objects the balsam must be diluted with benzole and the cover-glass gently laid on the top. The slide must then be dried at a temperature of about 72° C., the spirit being thus driven off. To ascertain if the process has gone sufficiently far, pick up from time to time with a splinter or match-stick a little of the balsam exuded round the edges of the cover-glass. Directly the sample thus removed is cold, press it with the thumb-nail. If it is brittle, the whole balsam will become hard and firm on cooling, and the slide may be removed from the air-bath in which it has been drying.

If the objects are strong, like sand-grains, the balsam may be dried previous to use. A little is softened by heat, and the objects are allowed to sink in it on the slide. The cover-glass is laid on while all is warm, pressed down, and the slide is laid aside to cool. Care must be exercised to prevent bubbles from forming in the balsam or the mass from becoming too brittle and discoloured by over-heating.

Very often the pressure used in placing the cover-glass in position forces the loose objects outwards or to one side of the preparation. Mr. H. C. Sorby * recommends the following remedy:—"Having placed a small quantity of dissolved gum on the glass plate, the requisite amount of the deposit is taken and mixed with the gum and sufficient water to make it easy to separate the grains and spread them uniformly over the space which will afterwards be covered by the thin glass. The water is then allowed to evaporate slowly, and though much of the gum collects round the margin, by properly regulating the quantity

* Presidential address to Royal Microscopical Society, 1877.

originally added, enough remains under the larger grains to hold them so fast that they are not squeezed out with the excess of balsam."

The gum should be in so small an amount as to be invisible, after the mounting is completed, except on an examination of the under side of the preparation.

It is scarcely necessary to remind workers that the water used in any treatment of microscopic objects must be distilled, since on the evaporation of ordinary water all manner of crystalline salts are deposited upon the objects.

To remove the balsam exuded round the edges of the cover-glass, the whole is allowed to become hard; the more prominent parts may then be chipped off readily with a blunt knife, the point of which must be kept clear from the edge of the cover; while the slide is finally and neatly cleaned with a tooth-brush dipped in methylated spirit. Wipe and dry at once with a soft duster.

Where **microscopic sections** are required, the preparation of the object is often a matter of considerable time. In the case of fragmental substances, an ingenious method suggested by Dr. Wallich * may be applied after a little practice. A small glass slip, or square cut from plate glass, is laid upon a metal plate over a spirit-lamp. A drop of nearly dried balsam is softened upon this by heat, and a plate of mica is laid on it, becoming thus cemented to the glass. The small objects of which sections are to be prepared are then embedded in further balsam upon the mica surface and arranged in any suitable position. When this balsam is cold and firm, the glass is used as a handle by which the objects can be held during grinding. A flat surface is then given to them as they lie in the balsam by rubbing with water on a hone made of Water-of-Ayr stone. When they appear properly rubbed down, the surface is washed and dried, and the glass is again lightly heated. As soon as the heat softens the lower film of balsam, that between the mica and the glass, the mica must be lifted up with a pair of forceps and turned over on to an ordinary microscopic slip on which a little balsam has been heating. The ground surface of the objects is now downwards, and they become fixed on cooling to the glass slip in the positions originally selected. When cold, use the new slip as a handle, flake off the mica lightly with a knife, since it now forms the surface-layer, and grind the newly exposed side of the objects in the same manner as before. When transparent sections have been thus prepared, wash, soften the balsam by gentle warming, and affix the cover-glass. For details concerning the making of

* *Ann. and Mag. Nat. Hist.*, 3rd ser., vol. viii. (1861), p. 58.

sections of delicate objects by such methods, see Chapman (*Scientific News*, vol. i., London, 1888, p. 452) and Stöber (*Travaux du laboratoire minéralogique de l'université de Gand*, 1899).

The same principles are involved in the preparation of sections of minerals and rocks such as are ordinarily examined by the geologist.* A conveniently thin chip is chosen, and a smooth surface is given to it on one side. For this purpose it is held in the hand and rubbed down with emery and water on a piece of plate-glass about 12 inches square. Emery, of the coarseness known as "60-hole," may be used at first; then "90-hole"; and then a carborundum hone, with two surfaces of different fineness. The specimen must be washed on transference from each grade of material to the next. When objects, such as the bars of a window, can be seen reflected in the prepared surface, this first stage of the process may be considered as finished. The chip is now cemented, the polished surface downwards, by means of Canada balsam† to a glass handle, preferably a piece of plate-glass about 1½ inches square. When the cement has become hard, no trace of bubbles should appear between the surfaces of the specimen and the glass. If present, they will gleam, as seen through the glass, like little mercurial globules, and must be got rid of by further heating and probably by the application of more balsam. The surface thus finished and cemented down forms one side of the section ultimately prepared.

The outer side of the specimen is now similarly ground away, the finishing touches being given with a carborundum hone or a Water-of-Ayr stone. Care must be taken in order that the central area, and not merely the edges, may become finally thin. Very delicate sections must be transferred at an early stage to the slip on which they are to be mounted, and finished on this instead of on the handle of plate-glass.

In ordinary cases, however, the section is examined under the microscope before removal from the glass handle, to see if it is sufficiently and uniformly thin. It is then placed in a bath of benzene for some five or six hours, at the end of which time it can be floated off from the handle and transferred carefully by a section-lifter (a bent piece of thin metal in a wooden handle) to an ordinary slip on which balsam is already heating. The covering and final processes are as described on pp. 128, 129.

* See articles in *Technics*, 1905.

† Prof. Rosenbusch recommends 16 parts by weight of Canada balsam to 50 parts of shellac, heated together for some time. The toughness of this allows very thin sections to be made.

To avoid the long grinding that must occur when chips are used, professional workers always employ in the first instance a lapidary's cutting disc, which is an iron disc "armed" from time to time by forcing diamond-powder into its edge. The diamond is mixed with a little olive oil and placed with the finger on the edge of the disc. The disc is then slowly rotated while a surface of flint or agate is pressed against it, the tiny splinters of diamond thus becoming set in the iron like the teeth of a circular saw. A well-armed disc will cut perhaps some thirty ordinary sections, and must be re-armed directly it ceases to give a clean cut and a sharp hissing noise when in motion. Discs styled "diamond-saws," armed for very prolonged work, are made by Mr. C. J. Whittle, 50 Congress Street, Boston, Mass., U.S.A.

The disc is preferably placed horizontally and rotated by a band working from a wheel driven and controlled by hand. The specimen is held in a clamp and is drawn against the disc by a weighted cord passing over a little pulley. The disc must be continuously lubricated by a little stream of soap and water kept running on to it from the tap of a vessel set above it; or it can be kept lubricated by soft soap, kept in a jar and painted on at intervals with a brush.

By such a machine thin and even large slices can be prepared, which require little grinding to transform them into microscopic sections. Sections, moreover, can be cut from minerals in special directions, by careful adjustment of the specimen in the clamp.* Small specimens can be held by being cemented on to a block of wood by means of the "electric cement" described on p. 21, the wood being then fixed in the clamp. Friable objects, such as pumice, must be saturated in hot balsam in a dish over a spirit-lamp or Bunsen-burner and allowed to become thoroughly cool. They may then, with care, be cut or ground like other materials.

Finally, it may be useful to mention that emery can be obtained in London for about 1s. 6d. per 7-lb. packet. Diamond-splint, which must be powdered in a steel mortar after purchase, costs about 10s. per carat, two carats lasting a considerable time. The iron discs used in lapidary's work are supplied by Messrs. Cotton & Johnson, of 14 Gerrard Street, Soho, London, W. Most amateurs, however, will find a machine rather a luxury than a necessity, considering the small number of sections they will require in the course of any year. While

* For a delicate method, see Stöber, *Bull. Acad. Roy. de Belgique*, 3e. série, t. xxxiii. (1897), p. 843.

it is of very great importance to have practice and confidence in the making of rock-sections, it is fortunate that now in some towns, especially in Germany, professional lapidaries are springing up, ready to relieve the geologist of work that is in the majority of cases tedious.

That the application of the microscope to the study of rocks is by no means a modern development has been already seen in our review of Cordier's classic investigations. Some older authors, notably Delesse, derived great advantage from the examination of polished surfaces of rocks under the microscope; and, such surfaces being commonly procurable in all countries, whether among the débris of ancient Rome or the workshops of Indian artists, it is of considerable profit to have studied at least a typical selection. Though polarised light cannot be employed, there are in some cases actual advantages over a thin section, inasmuch as the rock can be often examined by a low-power objective for a considerable depth, and the tridimensional character of the various objects and structures becomes realised. As a brilliant example of results gained in this manner, we may cite the plates and text of Delesse's *Recherches sur les Roches globuleuses*,* a memoir that should be looked at in this connection by all to whom libraries are accessible.

While it is now well for the beginner to study carefully a series of rock-sections under the microscope, these should never be considered apart from the rocks from which they have been cut. After understanding, with the assistance of the sections, the main points of structure, an immense amount of work can be done by powdering up a rock, sifting where necessary, and examining the fragments on a microscopic slip, first by reflected light, and then mounted in water or balsam under a cover-glass. The methods of Cordier (pp. 110-113) must never be forgotten, since the expert in the use of microscopic sections is apt sometimes to lose sight of the form of the solid mineral, and of all but its optical characters. The powdered rock naturally lends itself to the isolation and complete testing of its constituents (p. 113).

Some Works on Petrography and Rock-forming Minerals.

Fouqué and Lévy. Minéralogie Micrographique; Roches éruptives françaises. 2 vols., text and plates. Quantin, Paris, 1879. (Fine plates.)

Harker. Petrology for Students. 3rd ed., Cambridge, 1902. (Deals with rocks only; clear drawings of sections, and thoroughly modern.)

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* *Mémoires de la Soc. géol. de France*, 2me. série, t. iv., p. 301.

JANNETAZ. Les Roches. Rothschild, Paris, 1884. (Coloured plates of microscopic sections.)

LÉVY and LACROIX. (1) Les Minéraux des Roches. Baudry, Paris, 1888. (Contains an admirable plate showing the application of Newton's Colour-Scale to mineral-sections in polarised light.) (2) Tableaux des Minéraux des Roches. Baudry, Paris, 1889. (Reference tables founded on above work.)

MERRILL. Rocks, Rock-weathering, and Soils. Macmillan, 2nd. ed. (Regards rocks from a true geological aspect; excellent illustrations.)

REINISCH. Petrographisches Praktikum. Two parts. Borntraeger, Berlin, 1901. (Covers both minerals and rocks.)

ROSENBUSCH. (1) With WÜLFING, Mikroskopische Physiographie. 2 vols., 4te. Auflage. Nägele, Stuttgart, 1905. (With photographic plates of minerals as seen in sections.) (2) Hülfstabellen zur mikroskopischen Mineralbestimmung. Koch, Stuttgart, 1888. (Reference-tables, translated by Hatch, Sonnenschein.) (3) Elemente der Gesteinslehre. Nägele, Stuttgart, 2nd. ed., 1900. (An excellent general manual.)

ROSENBUSCH and IDDINGS. Microscopical Physiography of Rock-making Minerals. 4th American edition, revised. Wiley, New York; Chapman & Hall, London, 1900. (The photographs in the original work of Rosenbusch are produced.)

RUTLEY. (1) Rock-forming minerals. Murby, London, 1888. (A compact guide, including the higher applications of the microscope.) (2) Granites and Greenstones. Murby, 1894.

TEALL. British Petrography. Dulau & Co., London, 1888. (An invaluable work both for the text and the exceptional character of the coloured plates.)

WEINSCHENK. Die gesteinbildenden Mineralien. Herder, Freiburg-im-Breisgau, 1901. (An excellent compact guide for the geologist.)

ZIRKEL. Lehrbuch der Petrographie. 2te. Auflage, 3 vols., Leipzig, 1894. (The most complete work on rocks extant, dealing with their wider aspects as well as microscopic structure. The section on rock-forming minerals is equally admirable.)

CHAPTER XVI

THE MORE PROMINENT CHARACTERS TO BE OBSERVED IN MINERALS IN ROCK-SECTIONS, AND AS ISOLATED CRYSTALS UNDER THE MICROSCOPE.

It is well known that some minerals, such as magnetite, are opaque even in the thinnest sections yet prepared. Hence their characters must be studied by reflected light, which may conveniently be concentrated on their surface by an ordinary condenser on a stand, or by fitting up a pocket-lens so that it can be moved about upon an upright rod. The annexed sketch (fig. 16) is a suggestion for such a contrivance; a stout brass wire is fitted into a steady base, and a large cork slides up and down upon it. A second wire, also thick, so as to present a good surface, is bent at right angles; one end is thrust through the cork and the other carries a second cork, projecting out sideways, which can thus be moved in three directions. A part of this cork is cut away so as to form a slit, into which the handle of the lens fits and in which it is held by tightness. The same sort of arrangement may be useful for holding a lens in various positions when small loose objects are being examined by this instrument alone.

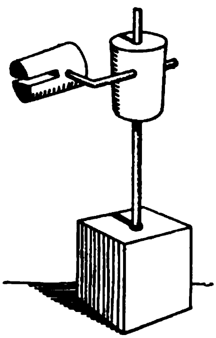

Fig. 16.

The characters that can be studied in *opaque* minerals are the form of the sections, the colour and lustre by reflected light, the cleavages (which often appear as black lines or cracks) and the products of decomposition that occupy the cracks or surround the crystal.

The characters of *translucent* minerals may be separately treated as follows :—

Form.—In rock-sections allotriomorphic crystals, or those that are bounded merely by abutting against neighbouring forms, are so common that the worker is at the outset apt to feel discouraged. The idiomorphic crystals, with their proper boundaries, in which he has so delighted during his mineralogical studies, are found to be, as it were, interesting curiosities when compared with the mass of the crystalline substances with

which he has to deal in rocks. But he soon realises that sufficient traces of regular outline frequently remain from which he can build up some well-known form; while in the lavas a number of sections are so sharp and satisfactory that he can determine the angles between various planes, compare one result with another, and picture to himself the complete crystal from some ten or a dozen scattered sections in a slide. For the correct appreciation of the objects thus seen under the microscope a knowledge of the solid forms of minerals and mineral-aggregates is obviously necessary; the study of "micropetrology" becomes otherwise something artificial, extra-natural, and is liable to be looked on with hesitation by workers accustomed to rock-masses in the field.

Just as no mountain-mass can be described by a stranger from a number of hand-specimens, however beautiful, so no rock can be adequately described from isolated microscopic sections. Again and again the observer will pass from his section to the solid specimen, and from this, in memory at any rate, to the great mass of which it formed a part. Even in his choice of descriptive terms, he will remember that nature is tridimensional, and that the object regarded by him under the microscope as a "plate" or "lath" may be of considerable thickness in a direction perpendicular to the section.

Having determined by a series of optical tests that certain sections in a slide belong to the same mineral, some fair deductions may be made as to the nature of the solid form. A fundamental enquiry is, however, how has the rock-section been cut with regard to any structural peculiarity of the mass? Thus a foliated rock will yield elongated and even wisp-like sections of its minerals if cut perpendicular to the foliation-planes, while more or less expanded lenticular forms will appear in slides prepared parallel to these planes. A rock, again, in which the minerals have been arranged by flow may ordinarily show a number of prismatic outlines; yet a section perpendicular to the direction of flow may represent the prismatic rods as square or almost circular areas, suggestive of cubes or granules. If, finally, the minerals so arranged are prisms, the three axes of which differ considerably in length, the majority of sections may appear as fairly short "laths" in one slide, as long ones in another, and as broad plate-like forms in a third. The annexed diagrams (fig. 17) will aid in making this matter clear.

When, however, the rock-specimen presents no peculiarities of structure, when in all aspects it looks reasonably similar in constitution, a single slide will enable one to ascertain the

general forms of the minerals that it contains. This is the case with most granitic and microgranitic rocks, and with very many of the lithoidal lavas. In these, if all the sections of one mineral appear approximately circular, as is the case with small leucites, garnets, &c., the true form must be granular or spheroidal. If rectangular sections and hexagonal "plates" are associated, we are dealing with a mineral that crystallises in

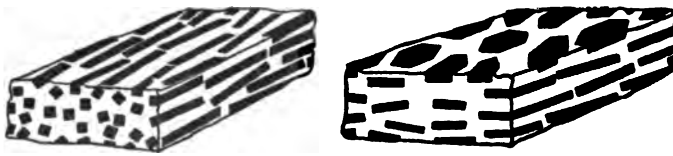

Fig. 17.

hexagonal prisms. If square sections predominate, with a few rectangles and triangles, the true form is likely to be a cube; if hexagons and squares abound, coupled with optical characters pointing to a mineral of the cubic system, that mineral has developed in rhombic dodecahedra or octahedra. Hexagons, puzzling at the first sight, are thus common in sections of well developed magnetite. The icositetrahedron, as in leucite, tends to produce octagonal forms.

In the case of ordinary prisms with a long vertical axis, optical tests must as a rule be applied before they can be referred to one system or another. But the cross-sections, and especially those which are believed to be perpendicular to the principal axis, must be very carefully studied, and special slides may have to be prepared so as to include as many of these as possible. The angle between the traces of the prism-planes is of fundamental value.

In the measurement of angles, the cross-wires and graduated stage come into service. In dealing with this and other questions, the rotation of the object is spoken of, since the description of such operations can easily be translated by those who work with a fixed stage and rotating eye-piece, cross-wires, and polariscope. In all ordinary instruments, then, the point of junction of two edges of a crystal-section is made to coincide, by moving the slide upon the stage, with the point of intersection of the cross-wires in the eye-piece. One of the edges is then brought, by rotation of the stage, into coincidence with one of the wires, and the angle indicated by the index on the margin of the stage is noted. The stage is then rotated until the other edge in question coincides with the same wire. The angular

movement undergone by the stage gives, according to the direction of rotation, either the angle between the two edges or the supplement of that angle. Of course if the two edges to be examined are separated by an intervening edge or a broken part of the crystal, their point of intersection, if produced, can be approximately fixed by the eye and brought into the centre of the field.

A number of such measures, and a number only, unless special optical tests have given proof of the crystallographic position of the section, will ultimately give a very good idea of the angle between particular faces of the solid form.

While the best evidence of the presence of twin-crystals lies in their effect on polarised light, yet the re-entrant angles characteristic of many such forms occasionally appear in sections. Crystals are, however, so often grouped together in irregular aggregates that re-entrant angles are by no means a sure sign of twinning. Occasionally, as in the little rutiles of some altered rocks, the whole form of a twin-crystal can be made out, the geniculated forms being in this case highly characteristic, lying as they do embedded in the thickness of the slide.

The outlines of crystals often become injured by the action of the fused vitreous matrix on them. This corrosion takes place mainly on the surface of the crystal, as in quartz, or causes the whole interior to become penetrated by glass, as in some pyroxenes and many felspars. The ramifying mesh of intruded glass shows in sections as a number of apparently isolated knots and "enclosures;" but careful tracing of their origin among many examples proves that they are in reality connected with one another by delicate filaments or sheets of the same material (see figs. 35 and 37). Stresses set up either during or after the consolidation of a rock will also tend to destroy the original outline of crystals. They may thus become broken and even ground to powder, or deformed and drawn out into almost unrecognisable wisps.

Still more interesting and remarkable, however, is the evidence afforded by the microscope of the reconstruction and growth of crystals. Thus, by additions made at periods long subsequent to the consolidation of the rock, worn, injured, or imperfect crystals may be restored or raised to more or less perfect forms. In other cases, the additions may be made to porphyritic crystals during the final consolidation of an igneous rock. The literature of this "regeneration of crystals" has grown of late years. The reader should consult a paper by Prof. J. W. Judd,

"On the growth of crystals in igneous rocks after their consolidation" (*Quart. Journ. Geol. Soc.*, vol. xlv. (1889), p. 175).

We figure here two examples (fig. 18), one of felspar and one of hornblende; in the latter case the interspaces between injured and shifted crystals have been filled up, as it were, by healing material, which has similar cleavages, and which is optically continuous with the original material on one side of the crack or on the other.

Cleavage. — The movement of crystals in rocks, and the stresses to which they are subjected, tend to reveal the cleavage of minerals by producing one or more series of fairly regular cracks. In sections these are distinguished without much difficulty from the more irregular lines of fracture that traverse almost all the minerals. Decomposition often starts from the cleavage-planes.

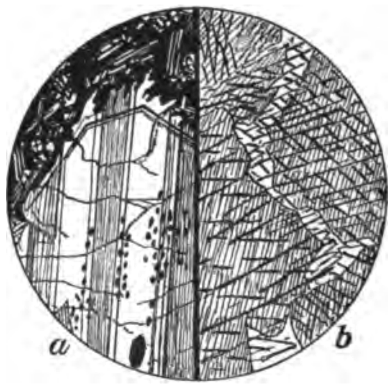

Fig. 18.—*a*, Plagioclase in dolerite—Tynemouth Dyke, Northumberland. × 14. *Nicols crossed.* The crystal has been enlarged by secondary outgrowths into the hemicrystalline groundmass, and the repeated twinning has been exactly reproduced. *b*, Hornblende in diorite—near Grands Mulets, Mt. Blanc. × 40. The brown crystals appear to have been shifted one against the other, and the intervening irregular areas have become filled up by colourless secondary outgrowths from one side or the other in continuity with the original crystals.

The cleavage-cracks are more or less clearly developed according to the character of the mineral, and this fact is of determinative value. Thus the cleavage of epidote is cleaner and sharper than that of pyroxene; the rectangular cleavage-system of olivine is very rarely apparent; quartz exhibits no cleavage, while felspar commonly does so in a very regular manner. An oblique illumination and a high power often prove a mineral to be cleaved which otherwise appears uniform and unbroken.

An appearance of cleavage under the microscope, and actual separation into lamellæ in the mineral specimen, often arise from the development of minute platy products along "solution-planes" in the crystal. This "pseudo-cleavage," a character

superinduced by alteration, is very marked in the orthopinacoidal separation-planes of diallage.

Enclosures.—Though any mineral may take up at the time of its formation enclosures of the matrix from which it is derived, or may shut up within itself pre-existing crystals, yet the nature and arrangement of such enclosures should be carefully studied. The regularly grouped plates already referred to, which there is excellent reason for classing as secondary products, will be dealt with below under the head of "Schillerisation;" but in addition to them there are often crystalline or amorphous bodies, and minute cavities containing gas, liquid, or glass, which may have been included at the time of consolidation.

Glass-enclosures containing bubbles may frequently be distinguished from liquid-enclosures by the immobility of the bubble and the occurrence of cracks or products of devitrification in the clear substance surrounding it.

Liquid-enclosures occur in various minerals, and are especially abundant in the quartz of granitic and metamorphosed rocks. They should be studied with a power magnifying 500 diameters, and the smallest will be found to possess the most active bubbles. In the case of some larger ones, the movement of the slide will cause the bubble to shift its position and thus prove the liquidity of the material; but as a rule it is the minute enclosures which will, after a little practice in observation, repay the worker in a brilliant and most satisfactory way. Gentle heating of the section will often aid in bringing about the unstable conditions which cause the movement of the bubbles. When the liquid has originally been a saturated solution, crystals may have separated out in it as it passed into a cold condition (fig. 19, *b*).

Ample observations have been made of late years, and may be repeated in any good collection of sections, to prove that liquid-enclosures often arise in minerals by solution acting within them long after they have consolidated. It seems impossible otherwise to account for the strings and bands of "enclosures" that run continuously from grain to grain in some altered sandstones (quartzites), or in the secondary quartz filling the cavities of ancient lavas (fig 19, *a*). Indeed, the more the problem of crystal-growth and crystal-dissolution is studied, the more difficult it becomes to point to this structure or that as undoubtedly fundamental and original.

Schillerisation.*—In addition to the enclosures of glass and

* See Prof. Judd, "On the Tertiary and older Peridotites of Scotland." *Quart. Journ. Geol. Soc.*, vol. xli. (1885), p. 383; also *Mineralogical Mag.*, vol. vii., p. 81.

liquid, which are occasionally seen under the microscope to possess regular outlines, and to represent, in fact, the infilling of negative crystals, there are included in certain minerals a host of bodies that similarly owe their form to the crystalline substance round them. The stages in the development of these minute plate-like "enclosures" have been worked out in a series of papers by Prof. Judd in the *Quarterly Journal of the Geological Society* and the *Mineralogical Magazine*. They have long been known in sections of the massive hypersthene of Paul's Island, and have been conjecturally referred to various mineral substances. Prof. Judd regards them as secondary developments of "mixtures of various oxides in a more or less hydrated condition, such as hyalite, opal, göthite, and limonite." They appear with marginal ramifications, or with one or more definite edges developed, or finally as accurately bounded negative crystals. The planes of chemical weakness along which they are produced become lustrous, as in hypersthene or diallage; they also impart the well known play of colours to the surfaces of certain felspars. This character of minerals, termed *schiller* by German writers, has led Prof. Judd to introduce the word "schillerisation" for the process by which the minute plates are developed. In studying the characters of various mineral species under the microscope, we shall see the importance attaching to certain well-marked schillerised types.

Fig. 19.—*a*, Quartz in altered rhyolite—Digoed, near Penmachno, N. Wales. × 40. The granular quartz is of secondary origin, occupying a cavity; liquid-enclosures have developed in strings which run continuously from grain to grain, proving that they are posterior to the quartz. *b*, Liquid-enclosures with bubbles and cubic crystals separated from the super-saturated solution. In quartz of tourmaline-granite—Great Staple Tor, Dartmoor. × 320. *c*, Structures produced by schillerisation in labradorite — Labrador. × 80. Three series of regularly arranged plates are seen in all stages of development. The plates practically perpendicular to the section appear as thin lines. Bands of liquid-enclosures also traverse the crystals, but not along regular planes.

It must be noted that the parallelism of the products of schillerisation can be observed only in sections across the solution-planes on which they are developed. Thus some sections will show only a few scattered negative crystals, like little plates lying apparently hap-hazard. But some other section of the same mineral will show these plates edgewise, when they will resemble lines, and the regularity of their disposition will be at once apparent (fig 19, *c*).

A mineral may become schillerised throughout, or the phenomenon may appear only in patches. Attention is commonly called to it, even under a 1-inch power, by the fact that the products are coloured, being often pink-brown or transparent red.

Zoned Structure.—Crystals are often seen to be built up of successively formed layers, producing concentric zones in sections. The slight differences in composition that may occur in adjacent zones, and the consequent difference of refractive index, causes a fine line of junction to appear between them, especially when the light is sent obliquely from the mirror. These zonal lines are parallel to the outlines of the crystals, and must be distinguished from cleavage-cracks or the composition-planes of twin-crystals, which will run right across the crystal parallel only to certain planes.

The surfaces of the successive coats by which a crystal may be thus built up may become covered with foreign particles, which will appear as zonally-arranged enclosures in the sections. Polarised light may also reveal zoned structure, owing to occasional differences of optical behaviour in the various zones.*

Refractive Index.—Since Canada balsam, the medium commonly employed in the mounting of rock-sections, has a maximum refractive index of 1·549, or, in practice, of 1·540, light passes freely from it to the interior of minerals having a similar index, and from these again to the upper film of balsam. They thus appear clear and with smooth surfaces. Quartz, with a refractive index of 1·547, is an excellent example of this class. It is thus said to show no relief.

But many other substances, with higher mean indices of refraction, exhibit the roughnesses and irregularities of their ground surfaces where the light passes from them to the balsam or the reverse. The mirror should be set obliquely, or a stop-lens may be used. It is quite as convenient to place the finger a little below the aperture of the stage, so that the light reaching the section consists of the oblique rays from the margin of the mirror only. Garnet will show this "pitted" effect in a most

* See on this matter Lévy and Lacroix, *Les Minéraux des Roches*, p. 85.

conspicuous manner. Where a mineral of high refractive index is surrounded by others of a lower index, its boundaries will appear as sharp and dark lines, and it will seem to stand out in relief on the surface of the section.

Minerals with a refractive index much lower than that of the balsam are rare, but will of course exhibit the same effect.

Dr. F. Becke ("Ueber die Bestimmbarkeit der Gesteinsgemengtheile auf Grund ihres Lichtbrechungsvermögens," *Sitzungsber. der k. Akad. der Wissensch.*, Vienna, Bd. cii., 1893, p. 358) has given us a most refined and practical method of determining whether a mineral in a rock-section is of higher or lower refractive index than an adjacent mineral, or than the balsam in which the section is embedded (see Lévy, *Déterm. des Feldspaths*, pp. 59-63). The line of junction between the two minerals, or between one on the edge of the section and the balsam round it, is accurately brought into focus. A fairly high power should be used. The light should be thrown up obliquely from the mirror; or, as M. Lévy prefers, the converging lenses are employed, a diaphragm being added below them to cut off all but the rays from the central area. The common mirror, however, acts well in most cases.

The rays that come up through the substance of higher refractive index, and strike its surface of junction with the adjacent substance at an angle lower than that of total reflection, are all totally reflected, and are accumulated on the side of the substance of higher index. When the objective is slightly raised, a bright band is seen on that side—*i.e.*, within the border of the substance of higher index. *Lower* the objective below exact focus, and the rays seem to come from the other side—*i.e.*, the bright border lies in the substance of *lower* refractive index (the two uses of the word "lower" make the matter easy to remember).

This observation detects differences of index as small as ·009, and is capable of many practical and even elaborate applications, especially among the felspars and the felspathoids.

The numerical determination of the index or indices of refraction of a mineral fragment has been much facilitated by Mr. C. F. H. Smith's improved refractometer (*Min. Mag.*, vol. xiv., 1905, p. 83).

Colour in Ordinary Light.—This character is naturally diminished in importance by the thinness of the section; and the caution previously given as to the colour of minerals in mass is even more necessary here. Red felspars and bronze-like micas

will become colourless in ordinary sections; grass-green actinolite may behave similarly, while common hornblende retains tints of green or brown. In the case of minerals like the felspars above mentioned, where the colour is due to alteration, the transmitted light should be cut off and the section examined by light reflected from its surface. Cloudy products will often thus become visible, which impart their colour to the mass.

The phenomenon of pleochroism referred to on p. 89 naturally has considerable effect upon the colour of thin sections. The variability of the face-colours in the same crystal will cause striking differences in the appearance of a mineral according to the direction in which it is traversed by the section. Thus hornblende may be dark green and pale yellow-green in the same slide, and biotite will be of various tints from straw-yellow to rich red-brown.

Axis-pleochroism (see p. 90).—The light emerging from a Nicol's prism is regarded as vibrating parallel to the shorter diagonal of the prism. If we send this light from the prism through a section of a doubly refracting crystal, other than one perpendicular to an optic axis, it will be broken up into two sets of rays, unless the plane of its vibration is parallel to one of the vibration-traces of the crystal-section. It will in the latter case, however, give us a pure axis-colour for the mineral section dealt with; and, if this section has been cut so as to include the vibration-directions of the fastest and slowest rays in the crystal, the axis-colour thus observed will be one of those required in describing the characters of the pleochroism of the mineral. On rotating the section, or the nicol, through 90°, the other extreme axis-colour will be observed.

The mere fact that a mineral is pleochroic in its thin sections is of great determinative value. The polariser is brought into play beneath it and rotated; or the crystal-section is rotated by means of the stage above the polariser. If any change of tint is observable, the mineral is dichroic or trichroic, according to the system in which it crystallises; commonly it is said to be pleochroic. It is obvious that the most intense pleochroic changes will be seen in sections that contain the vibration-directions of the fastest and slowest rays in the crystal. An extreme case is that of tourmaline, where the plane polarised light undergoes in thicker sections almost complete absorption when vibrating in a direction perpendicular to the principal crystallographic axis. In biotite, again, sections perpendicular to the basal plane are extremely pleochroic, the maximum

absorption occurring under the same conditions as in tourmaline.*

On the other hand, the occurrence of non-pleochroic sections is no proof that the mineral itself is not pleochroic. Where there is only a slight difference between the velocity of rays vibrating respectively parallel to the two vibration-traces of the section, the axis-colours for this section may be indistinguishable; and where no double refraction occurs, pleochroism will be entirely absent. Thus basal sections of biotite show no pleochroism, however intense it may be in oblique or vertical sections; and the same must be true of all basal sections of indubitably tetragonal or hexagonal minerals.

Hence, when in the following pages the pleochroism of a mineral is stated to be strong or intense, the remark refers to its average character in hap-hazard sections, the true maximum intensity being looked for, as already stated, in special sections (see p. 143), and the effects being liable to great variation in sections of the same mineral lying in the same slide.

In some colourless minerals, such as calcite, the difference of absorption for rays vibrating in different directions may be so great that a twinkling effect is produced on the rapid rotation of the polariser beneath the section, by which means such minerals may easily be picked out.

The simple mode of observation of axis-colours by means of the single nicol was introduced by Tschermak in 1869.

Double Refraction.—If, however, we insert the analyser as well as the polariser, cross the nicols, and thus observe the mineral, we frequently see colours produced which are due to double refraction in the crystal and the interference of the rays of the two groups when brought to one plane of vibration in the analyser. The strength of the double refraction is expressed

* When the absorption is so great as to cause the light emerging from the crystal-section to consist practically of one and not two sets of rays, the other set being arrested, as in the case of plates of tourmaline, a curious effect may become noticeable when axis-pleochroism is being observed. The lower nicol and the absorbing mineral may act together as a complete polariscope; hence if the slide is thick enough to allow of the presence of a doubly-refracting mineral between the polariser and a layer of the absorbing crystal, interference-colours will be seen at this point without the interposition of the upper nicol. This effect is often brilliantly seen where the edges of biotite or tourmaline overlap quartz or felspar in the section. If the slide is rotated until the mineral acting as analyser is at its darkest, the effect due to crossed nicols is produced; this may be tested by inserting the true analyser above, when the colours already seen will remain unaltered, showing that the light has been already "analysed," and therefore comes through the upper nicol without further change.

numerically by $\gamma - \alpha$ (see p. 87), and the colours are *high* in Newton's scale if this figure is large, say ·040, and *low* if it is small, say ·005. A mineral giving high colours is said to have strong double refraction, the low colours indicating weak double refraction. These colours will also depend on the thickness of the section, and on the direction in which it has traversed the crystal; their intensity will depend on the position of the vibration-traces of the section with regard to the diagonals of the nicols.

Firstly, then, for comparative purposes sections should be of equal thickness.

Secondly, the most distinctive effects are gained from sections that contain the vibration-traces of the fastest ray and the slowest ray in the crystal.

Thirdly, the maximum brilliance of colour in any crystal-section is obtained when the vibration-traces are at 45° with the diagonals of the nicols.

The thicker the section of a mineral, the higher the colour yielded by it between crossed nicols; but, in ordinary thin sections. minerals of strong double refraction may easily be picked out from those of weak, by the difference of the tints exhibited.

Extinction.—But it is obvious that when the vibration-traces in the crystal-section lie parallel to the vibration-planes or diagonals of the nicols, no double refraction will occur. The rays from the polariser traverse the crystal-section without being divided and rotated; hence they reach the analyser unchanged and are totally rejected, just as if no mineral intervened. The section appears, therefore, dark; it has undergone extinction.

The vibration-traces in a crystal-section being always at right angles to one another, the section will become dark in four positions 90° apart during rotation between crossed nicols. These positions of extinction show us then, conversely, the positions of the vibration-traces in the section, and may be stated as occurring so many degrees away from some known line in the crystal.

For the reading of **angles of extinction** certain crystallographic directions are selected, such as the vertical axis—often indicated by cleavage—or the edge formed by the intersection of two particular planes. This selected direction is set parallel to one of the cross-wires of the eye-piece, and the reading of the graduated circle is taken. The stage is then rotated until the crystal is at its maximum darkness, and the angle through which it has been moved gives a measure of the position of extinction. In accustoming the eye to correctly estimate this position, it is well to take readings during a complete rotation, the

figures recorded differing, if the observations are accurate, by exactly 90°.

It should be noted that sections perpendicular to an optic axis of a biaxial crystal do not become extinguished during a rotation; such sections may easily be tested by the use of convergent polarised light (p. 151). There are also some few minerals in which the optic axes for light of different colours differ widely in position, or even lie in different planes. Hence the position of the bisectrices, which control the angles of extinction, cannot be stated for ordinary white light, and sections may be rotated between crossed nicols without at any time becoming actually extinguished.

Various optical aids have been applied to the measurement of extinctions. Thus a quartz plate cut perpendicularly to the optic axis, and giving, by rotatory polarisation, a particular tint between the nicols, is sometimes inserted above the slide. As long as the directions of vibration in the crystal-section deviate from those of the lower nicol, so long will the crystal impart a new tint to that part of the quartz plate which lies above it. But when the position of extinction is reached, the action of the crystal is *nil*, and the whole quartz plate resumes its uniform colour. The Bertrand eye-piece, a development of this method, is still more delicate and satisfactory in use. The quartz plate is made of four separate sectors, meeting at the centre of the field, two of them, through rotatory polarisation, rotating the ray to the right, and the alternate ones to the left, the four having between crossed nicols precisely the same tint. A crystal placed with regard to the polariser in any other position than that of extinction imparts opposite colours to the alternate sectors when brought into the centre of the field; and its vibration-traces are parallel to the diagonals of the lower nicol when the colour of the four sectors is restored.

In measuring the angle of extinction, every regard must be had to the direction in which the section has been cut. The most important cases to consider are those in which the form is prismatic and the section is judged to be parallel to the principal axis of the crystal.

In the *tetragonal* and *hexagonal* systems, all sections from the prismatic zone will become extinguished when their principal axis is set upright in the field between crossed nicols, and therefore also when this is placed horizontally. Such cases, where the directions of extinction are parallel to the edges of the

rectangular sections, and thus to the axes of form, are said to possess **straight extinction**.

In basal sections of crystals of these two systems, the velocity of rays vibrating in all directions is equal, and hence no effect is produced on polarised light. Such sections are, in fact, perpetually extinguished, except where rotatory polarisation occurs.

In the *rhombic* system, all sections from the prismatic zone possess straight extinction.

The base and all macrodome and brachydome planes, though not necessarily rectangular in outline, extinguish parallel and perpendicular to the traces of the pinacoids when these are present, or to the axes of symmetry of the sections when they are bounded by traces of other planes. The straight extinction of all possible sections of the prismatic zone is a very distinctive character.

In the *monoclinic* system, the only section of the prismatic zone that possesses straight extinction is that parallel to the orthopinacoid. Hence all ordinary vertical sections show **oblique extinction**, which is commonly measured from the direction of the principal axis, as indicated by the traces of other planes of the prismatic zone or of the vertical cleavage-planes. The inclination of the direction of extinction to this vertical line increases gradually as the section departs from the orthopinacoid and approaches the clinopinacoid. Since in the latter plane, however, it may amount to only some 4° or 5°, certain monoclinic minerals may be set down on hasty observation as rhombic.

The orthodomes and the basal plane behave like the domes and base in the rhombic system, but the clinodome extinguishes obliquely.

In the *triclinic* system there is no fixed relation between the directions of extinction and the axes of crystallographic form.

Optical Sign.—When, by observation of the directions of extinction, the directions of the vibration-traces in a section have been found, it often becomes of importance to determine which of these belongs to the fast and which to the slow ray. By the use, moreover, of several sections of a biaxial mineral, the relations of its principal vibration-directions (corresponding to rays of greatest, mean, and least velocity) to the crystallographic axes may be determined. The importance of these points for determinative purposes, in the case of minerals otherwise resembling one another, may be seen from the remarks on p. 88.

The only means of determining the character of the vibration-

directions to which we need here refer is that involving the use of the quartz wedge. This is so cut that its longer axis is parallel to the optic axis—*i.e.*, to the longer axis of the optical indicatrix—of the original crystal of quartz. The slowest-ray vibration-trace is thus parallel to the length of the wedge, and the fastest-ray trace perpendicular to it. When the wedge is placed with these traces at 45° to the diagonals of the crossed nicols, and is moved over the field of the microscope between them, a series of bands of colour will be seen crossing it, rising in Newton's scale towards its thicker end. These are, of course, the interference-colours due to the particular thickness of the wedge at any point; their cause is admirably stated in Groth's *Physikalische Krystallographie*, ed. 3, pp. 33-44.

For the determination of the nature of either of the vibration-traces in a crystal-section, the section is placed in a position of extinction and then rotated through 45°. The quartz wedge is then moved above it, either across the stage or through a special slot, so that the longer direction of the wedge lies parallel to the direction of extinction that has to be determined in the crystal. If this direction is also the slow-ray vibration-trace in the section, the colour due to the quartz wedge will rise, as if the wedge became thicker where it overlay the crystal. If, on the other hand, the direction is the fast-ray vibration-trace, the colour will be lowered, and sooner or later, as the wedge continues to be inserted, *compensation* or blackness—usually a grey effect—will result. If the wedge is still further inserted, the colours which the mineral has just displayed in a descending order will be exactly repeated in ascending order, and this repetition equally on each side of the position of compensation is, as M. Lévy points out, the best possible proof that compensation has really occurred. Test the section now by inserting the wedge along the other vibration-trace. The colour of the section will rise continuously, and no darkness due to compensation will occur.*

For minerals with very strong double refraction, such as zircon, a steeper wedge than usual will be required. Dr. J. W. Evans's arrangement of two quartz-wedges with their optic axes perpendicular to one another (*Min. Mag.*, vol. xiv., 1905, p. 91) has many useful applications.

Twin-crystals.—Except in certain sections, the two halves of a simple twin, or the adjacent lamellæ of a repeated twin, will give

* The two colour-effects can be seen simultaneously by means of Stöber's double quartz plate (*Zeitschr. für Kryst.*, Bd. xxix., 1897, p. 22).

different colours between crossed nicols, and will have different angles of extinction (fig. 18, *a*). The polariscope indeed at once reveals the composite character of many crystals in which twinning would otherwise be undetected. Cases of cross-twinning, as in microcline, also occur. The surface of junction of the parts

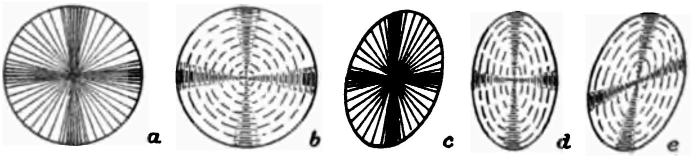

Fig. 20.

of a twin is seen under the microscope to be often step-like or even irregular; and in cases of repeated twinning the lamellæ are sometimes wedge-shaped, and do not run from end to end of the crystal-section.

Aggregates.—Ordinary aggregation must be distinguished between crossed nicols from twinning by the absence of regularity in the grouping of the constituent parts. A false effect of regularity is often set up where a mass is composed of fibres lying in all directions. Between crossed nicols, the fibres that happen to lie with their vibration-traces at 45° to the diagonals of the nicols show their brightest interference-colours, and catch the eye unduly. These fibres clearly form two sets, perpendicular to one another; and thus the illusion of a rectangular meshwork arises. If the stage is rotated, however, the two series of bright fibres give way continually to others, thus changing their directions in the slide.

When, however, a globular aggregate, as so often happens, is composed of a number of minute prisms, whether arranged radially or tangentially, a black cross will result between crossed nicols in ordinary polarised light, from the fact that the components lying in the positions of extinction all become dark at the same time (fig. 20, *a* and *b*).

If the directions of extinction agree with the axes of form, the arms of the cross will appear upright and horizontal in the field. If such an aggregate is ellipsoidal, but still built radially, the black cross will be unaffected by rotation of the stage (fig. 20, *c*); but if built by tangential additions, its arms approach or recede during rotation (fig. 20, *d* and *e*).

If the aggregate is built up of irregularly curving tufts and

fibres, several dark arms may appear, altering their forms, as well as their positions, during rotation.

Isotropism.—If a section remains equally dark between crossed nicols through a complete rotation—45 degrees is in reality sufficient—it is said to be *Isotropic*. Such bodies are:—

1. Amorphous and colloid, such as glass or opal.
2. Minerals of the cubic system, the velocity being the same for rays propagated in all directions, and no double refraction occurring.
3. Basal sections of minerals of the tetragonal and hexagonal systems.

In nature very few bodies are absolutely isotropic, owing to the stresses to which they are subjected in the earth; but the test is a very valuable one in picking out cubic minerals. In cases where the section is truly isotropic, but may yet belong to a uniaxial mineral, the use of convergent polarised light (p. 151) will set the question at rest, no black cross being obtained if the substance is really cubic.

Distortion and Anomalies.—The geologist must be prepared to find himself continually confronted by difficulties over which he can have no control. Even in estimating extinctions, bending of or pressure on the crystal may interfere with the results of this comparatively simple operation. Such distortions frequently occur, and one end of a crystal will be seen to give a totally different colour between crossed nicols from that given by the other. A crystal in which strains have been set up will sometimes send a wave of extinction from one end to the other during rotation. Hence in all refined observations the object must be very cautiously selected.

The anomalous double refraction of minerals of the cubic system is now well recognised, and is probably accompanied, as in leucite, by a true external reduction of symmetry. To exclude garnet, or haüyne, or even the much discussed leucite, from the cubic system on account of their optical behaviour and anomalies of form would be the first step towards the abolition of the system or to the admission that most cubic minerals are dimorphous. It would seem that symmetry so complete and exacting is unable to survive amid the varying temperatures and pressures that assail crystals from the first moment of their consolidation.

Ordinarily, however, the anisotropism of these anomalous cubic crystals reveals itself in tints of a very low order—in fact, the grey and white at the opening of the scale. Only in sections of some millimetres in thickness is coloured polarisation conspicuous.

Similar strains disturb the optical characters of minerals when viewed with convergent light; so that the observations to which we now proceed must be made on a number of sections of the same mineral in a slide before accurate conclusions can be drawn.

Uniaxial and Biaxial Crystals in Convergent Polarised Light.—The chief use of the sub-stage condenser in dealing with rock-sections is the determination of the uniaxial or biaxial character of doubly refracting minerals. A mineral-section is selected with the low power which appears suitable from a consideration of the probable position of the optic axis or the optic axial plane. Having been moved into the centre of the field, a high power, preferably an eighth-inch, is brought to bear on it, and the condenser is adjusted so as to converge the rays within the crystal. The nicols are crossed and the eye-piece is removed, the eye probably requiring to be held at a little distance from the top of the tube. As already mentioned, a lens may be used above the objective that will bring the optic axial figure within the focus of the eye-piece, which is thus retained; but it is noteworthy that observers of great eminence have preferred the smaller but brighter results given by the simple observation down the tube.

Rotate the stage, and, if the section is at all favourably cut, a dark shadow will move across. Some minerals with a strong double refraction, such as epidote, will show in addition coloured rings even in thin sections. The thicker the section, the more of these iris-tinted rings will appear within the field.

The indications of the rings and shadows, subject to the cautions given under the last heading, may be stated as follows.

a. Uniaxial Minerals.—1. An isotropic section should, if possible, be selected—*i.e.*, one perpendicular to the optic axis. In the case of quartz, owing to rotatory polarisation, thick sections thus cut show a colour, which, however, does not become extinguished on rotation of the section.

A section perpendicular to the optic axis will show a black cross, which is unchanged on rotation. Sometimes coloured circles may be seen round it. The arms of the cross are parallel to the vibration-planes of the nicols (fig. 21, *a*). The microscope should be tested on a good section of calcite, devoid of flaws, since little errors in the construction of the condenser may cause the cross to divide at the centre during rotation as if the mineral were biaxial.

2. If the section is oblique to the optic axis, the rays traversing it parallel to that axis may still be able to enter and emerge from the objective. In this case the centre of the black cross

will appear, but will not be in the centre of the field, and will shift its position as the stage is rotated, thus moving round in a circle (fig. 21, *b*).

3. If the section is still more oblique to the optic axis, the centre of the black cross will lie outside the field, and only one

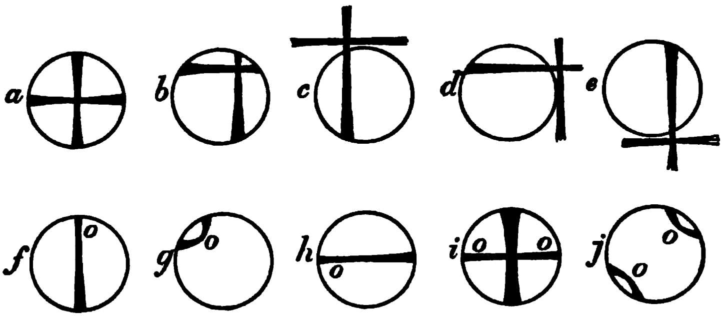

Fig. 21.

of its arms will become visible at a time. Thus on rotation a black bar will move across the field, keeping in a vertical position, followed by one moving across in a direction at right angles to the former, thus keeping in a horizontal position; when this has disappeared, the third arm appears, moving like the first; and then the fourth, moving like the second. The absence of deflection in the dark bars is the point to be especially noted (fig. 21, *c*, *d*, and *e*).

Strain will destroy this regularity; some biaxial minerals, on the other hand, have so small an optic axial angle that the figure given by them scarcely deviates from the black uniaxial cross throughout a complete rotation.

β. *Biaxial Minerals.*—1. If cut so that the rays parallel to an optic axis reach the eye, the section shows a dark bar which swings round on the rotation of the stage, moving in an opposite direction. At the same time it becomes hyperbolic, straightening itself out in four positions during rotation. Coloured rings may possibly surround the optic axis, as above described.

Since the bar becomes straight when the trace of the optic axial plane is parallel to the vibration-plane of either nicol, and since the bar then lies along this trace, it may be of service as giving the position of the optic axial plane in the crystal.

When the section is oblique to the optic axis, *o*, through which the black bar passes, this moves round the centre of the field (fig. 21, *f*, *g*, and *h*).

2. If the section is more oblique to the optic axis—*i.e.*, if it approaches more nearly to a direction perpendicular to one of the bisectrices—the dark bar may escape from the field during rotation.

3. If the section is perpendicular or approximately perpendicular to one of the bisectrices, preferably the acute bisectrix, a black cross will appear when the optic axial plane is parallel to the vibration-plane of either nicol. Rotation at once causes a separation of the cross into two hyperbolæ, though in a few minerals this separation is very slight (fig. 21, *i* and *j*).

In the examination of thin sections, both the optic axes of the figure in the case we are considering generally lie outside the limits of the field, and hence, when the optic axial plane is at 45° to the diagonals of the nicols, both the hyperbolæ are carried out of sight. Their convex sides always face the bisectrix which emerges in the field, and the thinner arm of the black cross that can be formed by them lies along the trace of the optic axial plane.

This occurrence of two dark curves sweeping across the field and uniting at every 90° of rotation to form a cross is one of the best features by which biaxial crystals can be determined. In default of so good a figure, the curvature of the single bars that come into view must be noted, in opposition to the permanent straightness of those of uniaxial crystals. The typical figure given by biaxial minerals may be well studied in muscovite, and, commencing with a thick piece, the specimen should be thinned down until the hyperbolæ are accompanied by the merest trace of coloured rings.

In certain special cases, finally, where it is known that the section is perpendicular to the acute bisectrix, the optical sign of the crystal can be simply determined. The trace of the optic axial plane is set at 45° to the diagonals of the nicols; since it is one of the vibration-traces of the crystal-section, determine with the quartz wedge in plane polarised light whether it corresponds to the ray of greatest or least velocity (see p. 147). If greatest, that is to say, if compensation occurs when the wedge is thrust along this direction, then the vibration-trace perpendicular to the optic axial plane is that of the slow ray in the section. Since this latter direction is always the vibration-direction of the ray of mean velocity in the crystal as a whole, the acute bisectrix, the normal to the section, must be the vibration-direction for rays of least velocity in the crystal, which is, therefore, positive. If the experiment gives a reverse result, the crystal is negative.

CHAPTER XVII.

THE CHARACTERS OF THE CHIEF ROCK-FORMING MINERALS IN THE ROCK-MASS AND UNDER THE MICROSCOPE.

UNDER this heading are given the characters presented by common minerals as they occur in rocks, the order followed being alphabetical. The minerals of first importance are printed in thick type. Each description is divided into two parts :—

I. The most striking characters of the mineral as it appears embedded in the rock-specimen, with one or two additional notes.

II. The characters it exhibits in microscopic sections. Many of these characters can of course be observed in isolated grains (p. 132). The abbreviations used are as follows :—

Comp.—Chemical composition.

Syst.—Crystallographic system.

Form.—Ordinary form, or outlines in sections.

Cleav.—Cleavage.

Encl.—Enclosures.

Zon.—Zone-structure.

Refr. Index.—Average index of refraction (determined with yellow light). The figures are mostly those given by Lévy and Lacroix, *Tableaux des Minéraux des Roches.*

Colour.—Colour as seen in ordinary light. Variations according to the face viewed (face-colours). Appearance of alteration-products.

Pleo.—Pleochroism as observed by means of the single nicol (axis-colours).

D. Refr.—Double refraction. This is "strong" when the difference between the greatest and least index of refraction in the crystal is large (say ·040), and "weak" when this difference is small (say ·005). In the former case we have "high" colours, in the latter "low."

Extinct.—Positions of extinction.

Opt. sign.—Optical sign; including character of the acute bisectrix, and its position.

Twins.—Characteristic twinning.

Actinolite.—A non-aluminous amphibole. Special points:—

I. Long prisms, distinctly green; often in radial bunches.

II. *Colour*—Pale green to colourless. *Pleo.*—Faint tints of green.

Note.—See Hornblende and Tremolite.

Ægirine.—See Soda-Pyroxenes.

Albite. —See Plagioclases.

Amblystegite.—See Rhombic Pyroxenes.

Amethyst.—Like quartz. Special points:—

I. Violet colour; occurs in cavities of rocks.

II. Pleochroic when the section is thick enough for the colour to appear.

Amphiboles. — See Actinolite, Anthophyllite, Hornblende, Soda-Amphiboles, Tremolite.

Analcime.—*Comp.*—Some varieties = $Na\,Al\,Si_2\,O_6 + H_2\,O$. *Syst.*—Probably cubic.

I. In cavities of rocks; colourless glassy-looking or opaque white icositetrahedra, commonly in groups.

II. *Refr. Index.*—Near leucite (1·487). *D. Refr.*—Sometimes anomalous, in grey and greyish-white tints; sometimes forms an isotropic ground-mass between other minerals.

Note.—Fuses easily, and gelatinises in $H\,Cl$. Compare leucite, which it resembles externally. If the substance is transparent in the mass, it is very probably analcime rather than leucite. Analcime may occur as a decomposition-product of nepheline.

Anatase.—*Comp.*—$Ti\,O_2$. *Syst.*—Tetragonal.

I. Occurs as brilliant blue-black to black modified bipyramids, which, though commonly about 3 mm. long, catch the eye by their lustre on the surfaces of rocks. Is found sometimes on dissolving limestones or extracting the heavy minerals from sands.

II. *Refr. Index*—Very high (2·52).

Andalusite.—*Comp.*—$Al_2\,Si\,O_5$. *Syst.*—Rhombic.

I. Sometimes seen as well-marked grey or pink prisms in schistose rocks, nearly square in section, or merely rod-like and poorly bounded (specific gravity = 3·18).

II. *Form*—Small granular, as in Cornish granites, to rod-like, as in schists. *Refr. Index*—1·638. *Colour*—Colourless, or face-colours faintly pink or green. *Pleo.*—Remarkable, from palest

green to a brownish or pinkish red. Obscured in the imperfect specimens in schists. *D. Refr.*—·011.

Note.—See Chiastolite.

Anorthite.—See Plagioclases.

ANORTHOCLASE.—See Microcline.

ANTHOPHYLLITE.—*Comp.*—(Mg, Fe) Si O_3 with $Al_2 O_3$ at times (GEDRITE). *Syst.*—Rhombic.

I. Not known as a common constituent, but may assume importance when closely looked for. Occurs as groups of long prisms in some metamorphic rocks, and among the zones of secondary minerals in some altered gabbros.

II. *Form* and *Cleav.*—Practically the same as hornblende, but with rhombic symmetry. *Colour*—Colourless in examples at present known. *Extinct.*—Rhombic, *i.e.*, straight, extinctions. Soda-hornblendes and brown ferriferous hornblendes have, however, only a small angle of extinction.

Apatite.—*Comp.*—3 $Ca_3 P_2 O_8$ + Ca (Cl, F)$_2$. *Syst.*—Hexagonal.

I. Sometimes visible as yellowish-white streaks in metamorphic rocks, scratchable with the knife; but, despite its abundance, commonly too small for detection with the eye.

II. *Form*—Long prism, giving hexagons and acicular forms. Occurs as minute crystals included in the other minerals of the rock; rarely in larger prisms. *Cleav.*—Not seen. *Encl.*—Absent. *Refr. Index*—Higher than felspars (1·637). *Colour*—Colourless; no decomposition-products. *D. Refr.*—Somewhat weaker than felspars. *Opt. Sign*—Negative. (Fig. 27.)

Note.—Nepheline crystallises in shorter prisms, commonly contains enclosures, and readily decomposes, showing yellow-brown sections. Primary quartz does not occur in prisms in igneous rocks; quartz is positive.

Aragonite.—*Comp.*—Ca C O_3. *Syst.*—Rhombic.

I. Common in the deposits of warm waters (pisolitic grains, &c.) and as a constituent of the shells of many genera. Forms also radial groups in the cavities of altered rocks. Specific gravity = 2·93; calcite = 2·72. Slightly harder than calcite, which it consequently scratches. Michrochemical test, see p. 36.

II. *Form*—Prismatic, the compactness of grouping often veiling this in sedimentary rocks. *Refr. Index*—Higher than calcite (1·632). *Colour*—Colourless. *D. Refr.*—Colours like calcite. Optic axial plane, the macropinacoid. *Extinct.*—Rhombic extinctions. *Opt. sign*—The vibration-direction for the fastest ray coincides with vertical axis; it is the acute bisectrix, and

the mineral is thus negative. In calcite also the vertical axis is the vibration-direction for the fastest ray.

ARFVEDSONITE.—See Soda-Amphiboles.

Augite.—*Comp.*—$m(Ca,Mg,Fe)SiO_3+n(Ca,Mg,Fe)(Al_2,Fe_2)SiO_6$ (for constitution, see Groth, *Tab. Uebersicht*, 1898, p. 146). *Syst.*—Monoclinic.

I. Black and often short prisms, or granular groups between felspars. Sometimes dark or pale green. Cleavage-surfaces often visible. Slightly scratched with knife. Forms sometimes ophitic masses, and appears as if uniformly infilling the spaces between the felspars, or around granular olivines.

II. *Form*—Prismatic, with eight-sided cross-sections, both pinacoids being developed as well as the prism. Angle of the latter 87° (figs. 38 and 40). Vertical sections show the trace of one or both the characteristic half-pyramid planes. Often granular or ophitic. *Cleav.*—Prismatic, showing thus in cross-sections a series of cracks intersecting nearly at right angles. *Encl.*—Glass and crystalline enclosures fairly common. The schillerised forms pass over into diallage and "pseudo-hypersthene." *Zon.*—Common in large examples. *Refr. Index*—1·72. *Colour*—Typically yellow-brown to purplish-brown. Occasionally pale green. The more strongly green varieties are described under soda-pyroxene. *Pleo.*—Very slight, except in the soda-pyroxenes. *D. Refr.*—Fairly strong, the colours commonly being the pinks, yellows, and greens of the second and third orders. Optic axial plane is the clinopinacoid. *Extinct.*—On clinopinacoid 40° to 50° away from principal axis. Hence typically a large angle as opposed to hornblende. This is reduced in soda-pyroxenes. *Opt. sign*—Positive. The vibration-direction for the fastest ray points towards the obtuse angle that is usually seen in vertical sections—*i.e.*, that formed by the traces of a pyramid plane and the orthopinacoid. *Twins*—Fairly common, a number of repetitions arising towards the centre of the crystal, and an untwinned portion occurring on either side. Composition-plane the orthopinacoid.

Note.—Hornblende very commonly arises as a partial or complete replacement of augite, being developed from it by paramorphic change, the resulting pseudomorph being URALITE. The outline of the augite is, however, commonly not preserved, actinolitic needles spreading through the mass and projecting from it, or larger hornblendic forms appearing round about it and in most intimate connexion (fig. 27).

For allied pyroxenes, see coccolite, diallage, diopside, and soda-pyroxenes. Also rhombic pyroxenes.

Bastite.—A name at one time applied to the serpentinous and schillerised pseudomorphs after rhombic pyroxene that often

occur in serpentine-rock and sometimes side by side with but slightly altered augite.

I. Generally resembles diallage.

II. Generally resembles diallage. *Colour*—Pale brown or green, in the latter case often with separated granules of magnetite. *Pleo.*—Fair in the green examples. *D. Refr.*—Usually shows effects due to the presence of residual unaltered pyroxene. *Extinct.*—Rhombic; parallel thus to the cleavage and schiller-planes in most sections.

Biotite.—*Comp.*—$(H, K)_2$ $(Mg, Fe)_2$ (Al_2, Fe_2) $Si_3 O_{12}$ (after *Groth*). A typical and common ferro-magnesian mica. For general characters see micas. Special points:—

I. Commonly dark green or bronze-black. A very abundant constituent of igneous rocks, particularly in the syenite and diorite groups.

II. *Colour*—Brown or green; but sometimes colourless. The striking pleochroism gives dark basal sections (*i.e.*, those showing no cleavage), and far lighter vertical sections. The latter are very often straw-yellow, the former reddish-brown. Decomposes to green chloritic products. *Pleo.*—Intense in vertical sections, often yellow-brown to grey-brown; darkest tint when shorter diagonal of nicol is parallel to basal cleavage. Not perceptible in basal sections, the typical mineral being practically uniaxial. *D. Refr.*—Strong (·058). Colours seen only in very thin sections. Basal sections practically isotropic. Convergent light gives a nearly uniaxial figure. (Figs. 24 and 27.) Even when the section is in a position of extinction, light spots usually appear in it, owing to local bending of the mineral during grinding (H. S. Jevons, *Geol. Mag.*, 1893, p. 82).

Note.—Distinguished in rock from hornblende by lustre, platy character, and hardness; in section by single cleavage, ragged fibrous edges, the light spots above mentioned, and the fact that the basal sections are the darkest and show no cleavage. Compare notes on phlogopite. Biotite, like hornblende, is often altered, by the action of a hot enclosing magma, into mere black skeletal forms.

Bronzite.—See Rhombic Pyroxenes.

Calcite.—*Comp.*—$Ca C O_3$. *Syst.*—Hexagonal (Trigonal).

I. Recognised by its cleavage-surfaces and hardness (= 3).

II. *Form.*—Oval or irregular granules, fitting against one another, in veins or cavities, or forming the mass of a crystalline limestone. *Cleav.*—Rhombohedral, often bent by pressure, giving two or even three series of obliquely intersecting lines, which are very clear, and along which reflections often give rise to inter-

ference colours in ordinary light. *Refr. Index*—1·486 for rays vibrating parallel to optic axis, and 1·658 for those vibrating perpendicular to it. Hence the rapid rotation of the polariser produces a sort of twinkling effect, owing to the difference of "relief" (p. 141) shown by rays vibrating in different directions; and calcite can often thus be picked out in the preliminary examination of a slide. *Colour*—Colourless. *D. Refr.*—Very strong, so that colours of the fourth and higher orders are alone visible in ordinary slides, the tints being often practically white. *Opt. sign*—Negative. *Twins*—Very common, repeated, parallel to the negative rhombohedron, *x* ($01\bar{1}2$), the traces of their composition-planes running in many sections parallel to the cleavages. (Pl. II., fig. 1.)

Note.—See Dolomite and Aragonite, and fig. 23. For useful micro-chemical reactions, see p. 36.

Cassiterite.—*Comp.*—$Sn\,O_2$. *Syst.*—Tetragonal.

I. In some granites, in orange-brown to black-brown lustrous grains. Can be easily isolated by washing the powdered rock; test with the blowpipe.

II. *Form*—Prisms, squares, and granules. *Cleav.*—Distinct. *Zon.*—Sometimes zones of deeper colour. *Refr. Index*—Higher even than garnet (2·029). *Colour*—Yellow to red-brown, varying in patches in the same grain. *Pleo.*—Conspicuous in the browner parts. *D. Refr.*—Exceptionally strong (·097), but not so strong as in rutile. Pink and green colours of high orders. *Opt. sign*—Positive. *Twins*—Common, geniculated.

Chalcedony.—*Comp.*—$Si\,O_2$.

I. Blue-grey to browner and more flinty aggregates in the hollows of lavas, in limestones, and associated with flint and chert, which are in fact more massive varieties. Forms alternate layers with quartz or opal in agates. Not scratched by the knife.

II. *Form*—Radial aggregates or minute granules. *Refr. Index*—Very slightly lower than quartz (1·537). *Colour*—Colourless to brownish. *D. Refr.*—Like quartz; colours brilliant, of about first order. The aggregates consist of delicate fibres, in which the fastest ray vibrates parallel to the long axis. These are not, therefore, prisms of ordinary quartz.

Chiastolite.—A white variety of andalusite with enclosures of dark amorphous matter regularly arranged. In sections parallel to the vertical axis, bands of this dusky matter may be seen running down the length of the prism; in transverse sections, a

diagonal cross appears, commonly with a dark square at the centre and at each angle of the section. Or the accumulation of foreign matter at the angles may leave an interstitial white cross of the purer mineral towards the centre. The mineral commonly arises in slaty rocks as a product of contact-metamorphism.

Chlorite.—The name of a group of minerals composed of silicates of magnesia, ferrous and ferric oxides, and alumina, in various proportions, with much water. *Syst.*—Probably all monoclinic, though many approach the hexagonal system. Similar crystallographic characters occur in the mica group.

I. While resembling dark green micas, the chlorites are softer, being very easily scratched with the thumb-nail. Their lamellæ are less elastic than those of mica, and show more markedly the effects of injury and pressure.

II. *Form*—Hexagonal plates and fibrous-looking, fan-like, or spherulitic aggregates. Often develops from green amorphous masses in the cavities of rocks, or as a pseudomorphic product of ferro-magnesian minerals. *Clear.*—Basal, distinct. Often distorted by pressure. *Refr. Index*—About 1·6. *Colour*—Yellow-green to blue-green. *Pleo.*—Noticeable in sections showing cleavage; yellowish when the shorter diagonal of the nicol is perpendicular to the basal cleavage, and green when it is parallel to it. *D. Refr.*—Weak (·001 to ·014); colours mostly first order; a deep blue is characteristic. *Extinct.*—In many examples parallel to the cleavage; in some as much as 15° from the vertical axis (clinopinacoidal sections of clinochlore).

Note.—Compare green biotite and serpentine.

Chloritoid (see Ottrelite).

Chromite.—*Comp.*—(Fe, Cr) $(Fe_2, Cr_2)O_4$ (often with MgO and Al_2O_3). *Syst.*—Cubic.

I. Black grains and crystals, resembling magnetite, commonly in olivine-rocks.

II. *Form*—Granules, or squares and hexagons, derived from octahedra. *Colour*—Black and opaque unless especially thin, when it becomes a rich claret-brown. *D. Refr.*—None. Isotropic.

Note.—Compare magnetite. See also spinelloids.

Coccolite.—A granular ferriferous diopside. Occurs in some crystalline limestones. Colour various shades of green, almost or completely colourless in thin sections. See Augite.

Cordierite.—*Comp.*—$H_2(Mg, Fe)_4Al_8Si_{10}O_{37}$ (*Farrington*). *Syst.*—Rhombic.

I. Typical colour a delicate blue, inclining to grey; forms glassy-looking patches in some granitoid and gneissic rocks, and

may occur as prisms, though rarely, in lavas. Not scratched by the knife, but easily decomposed and becoming thus much softer.

II. *Form*—Mostly irregular grains. *Encl.*—Fibrous enclosures of sillimanite common. *Refr. Index*—1·536; hence shows no pitted appearance. *Colour*—Colourless to faint blue. Decomposition products greyish or yellowish-green. *Pleo.*—Though marked in thick specimens, feeble in ordinary sections. Bluish when the shorter diagonal of the nicol is parallel to base; pale yellow when it is parallel to vertical axis. *D. Refr.*—Colours commonly first order only. *Extinct.*—Rhombic.

Note.—See Pinite. Distinguished from quartz by biaxial character.

Diallage.—A common form of monoclinic pyroxene.

I. Conspicuous by its sub-metallic lustre when the rock is turned about in the hand. The lustrous separation-planes give it a "foliated" character, amounting, indeed, to a new cleavage parallel to the orthopinacoid. It cannot well be distinguished from bronzite, hypersthene, and bastite in the rock-mass.

II. Like the pale brown augites, but has, in all sections but those approaching the orthopinacoid, a series of strong striæ, which are the traces of planes of schillerisation. *Encl.*—Numerous brownish secondary enclosures on the separation-planes (fig. 30).

Note.—Diallage should now be closely linked with augite, crystals of the latter being at times diallagic on the edges. It passes very commonly into hornblende.

DIOPSIDE. *Comp.*—$Mg\,Ca\,Si_2\,O_6$. A pale green scarcely ferriferous monoclinic pyroxene, often colourless in sections. See Augite; also Olivine.

DIPYRE (see Scapolites).

Dolomite. *Comp.*—$Ca\,Mg\,C_2\,O_6$. *Syst.*—Hexagonal (Trigonal); almost isomorphous with calcite.

I. Occurs in cavities of rocks rich in calcic and magnesic silicates and may easily be mistaken for calcite. Curved faces of the rhombohedron frequent. Forms, in minute or coarser granules, whole masses of "limestone," which may be distinguished from ordinary limestones by higher specific gravity (2·85 about) and action with acids (see pp. 36 and 70).

II. Like calcite, but twinning is by no means common in rock-building forms. Well-outlined sections of rhombohedral crystals are characteristic in dolomite, but are rare in calcite (Pl. II., fig. 2).

ELÆOLITE (see Nepheline).

Enstatite (see Rhombic Pyroxenes).

Epidote, variety Pistacite. *Comp.*—$H\,Ca_2\,(Al,\,Fe)_3\,Si_3\,O_{13}$. *Syst.*—Monoclinic.

I. When in fair-sized crystals or grains, shows the char-

acteristic yellow-green colour. Occurs often as a decomposition-product in fibrous groups.

II. (see fig. 29). *Form*—Prismatic, but the plane of symmetry is perpendicular to the long axis of the crystals. Hence what appear to be cross-sections of the prism, with an angle of 115° 27′, must be read as bounded by the base and the orthopinacoid. Occurs very often as irregular granules, spreading through the rock where decomposition of lime-silicates has gone on. At other times colourless or coloured little prisms are seen projecting into cavities which have since been filled with pale green chlorite. *Cleav.*—Basal perfect, orthopinacoidal often good. Hence on the rhomboidal sections, which at first suggest a pale hornblende, there are at times two cleavages parallel to the outline; and a slight obliquity in the cutting will make the characteristic angle of epidote agree with that of the hornblende prism. *Refr. Index*—1·75, or almost as high as that of common garnet. *Colour*—At times colourless, but typically pale yellow or a faint yellow-green in which yellow largely predominates. *Pleo.*—Faint. *D. Refr.*—Stronger than common pyroxenes and amphiboles. Optic axial plane parallel to clinopinacoid and therefore perpendicular to the longer direction of the crystals. *Extinct*—Parallel and perpendicular to the edge formed by the base and orthopinacoid in sections parallel to these planes, and thus "straight" also in almost all the sections that look prismatic.

In clinopinacoidal (rhomboid) sections extinction is practically parallel to the trace of the orthopinacoid; in the rhomboid sections of an amphibole it would occur parallel to the diagonals. *Opt. Sign*—Vibration-direction for the fastest ray is nearly parallel to principal axis and is the acute bisectrix. *Twins*—Occasionally seen; composition-plane parallel to orthopinacoid.

Note.—Compare Zoisite.

Felspars (see Orthoclase, Microcline, and Plagioclases).

FLUOR-SPAR. *Comp.*—$Ca F_2$. *Syst.*—Cubic.

I. Occurs in altered rocks, sometimes with tourmaline; common colour violet, appearing in patches between the other minerals. Hardness = 4.

II. *Form*—Sometimes shows defined edges; generally irregular. *Cleav.*—Octahedral, perfect, the intersections at times suggesting calcite. *Zon.*—Coloured zones occasionally, somewhat imperfect and sporadically developed. *Refr. Index*—1·433; lower than that of the balsam. *Colour*—Colourless, but often with violet patches irregularly developed. This colour is characteristic in small grains that might otherwise remain undetected. *D. Refr.*—None. Isotropic.

Garnet. The name of a group of minerals, the composition of which may be stated as $(Ca, Fe, Mg, Mn)_3 (Al_2, Fe_2, Cr_2) Si_3 O_{12}$. *Syst.*—Cubic.

I. Commonly-red (Almandine and Pyrope); or pale brown (Grossularite). Not scratched with the knife. Forms dominated by the rhombic dodecahedron, often rounded. The other minerals of the rock are often bent round the hard resisting garnets, which produce an eye-structure and stand out like knots. The easy fusibility of common garnets is a guide in cases of doubt.

II. *Form*—In some lavas sharply outlined, but almost always in ovoid or spheroidal grains, small or large. These, in some "flaser-gabbros," form a zone around decomposing minerals. *Cleav.*—Not always seen; parallel to rhombic dodecahedron. *Encl.*—Common, of all kinds, sometimes regularly arranged. *Zon.*—Occasionally seen, as in the coloured zones of melanite (lime-iron-titanium garnet). *Refr. Index*—Exceptionally high, about 1·770. The outlines become thus very strongly marked where they come against most of the other minerals in a slide. *Colour*—Colourless to pink or brown (melanite). Commonly a pale but unmistakable pink. *D. Refr.*—Isotropic, but with fairly frequent anomalous double-refraction, showing grey tints. (Fig. 43.)

GEDRITE (see Anthophyllite).

GLAUCONITE (see p. 191).

GLAUCOPHANE (see Soda-amphiboles).

Graphite. *Comp.*—C.

I. Occasionally forms considerable beds and masses. Best recognised by characters stated on p. 71.

II. Opaque; steel-grey by reflected light, resembling granular magnetite.

Gypsum. *Comp.*—$Ca S O_4 + 2 H_2 O$. *Syst.*—Monoclinic.

I. Found in washings of clays; also as crystalline masses (gypsums of the Alps; alabasters). Scratchable with the thumb-nail.

II. *Form*—Commonly seen as little rhomboidal cleavage-flakes. The angle between the pyramidal and orthopinacoidal cleavages, which bound these forms, is 113° 51′, and is often useful for measurement. *Cleav.*—Clinopinacoidal perfect; the two cleavages above mentioned are also developed. *Refr. Index*—1·524. *Colour*—Colourless. *D. Refr.*—Low; beautiful clear colours. Optic axial plane is the clinopinacoid. *Twins*—Fairly common, on orthopinacoid, producing the "arrow-head twin."

HÆMATITE. *Comp.*—$Fe_2 O_3$. *Syst.*—Hexagonal (Trigonal). In sections shows clear orange-red plates, or granular patches associated with magnetite or decomposing ferriferous minerals. By reflected light characteristic red colour. See Limonite.

HAÜYNE. *Comp.*—$(Na_2, Ca)_5 Al_6 Si_6 O_{24} . S_2 O_8$. See Nosean. *Syst.*—Cubic.

I. Sometimes recognisable as blue or dark-grey crystals or granules on broken surfaces of lavas. Vitreous lustre when blue and fairly fresh.

II. *Form*—Hexagonal or square, resulting mainly from sections of rhombic dodecahedra. Often minute. *Encl.*—Abundant enclosures grouped in straight lines, often rod-like and at right angles to one another. Under a ¼-inch objective these appear like a black cross-hatching, which is particularly marked towards the centre of the crystal. *Zon.*—Often a darker or lighter zone at edge. Where the crystal is corroded, the dark zone often follows the outline and is thus seen to be a phenomenon of alteration. *Refr. Index*—About 1·5, or lower than the balsam, but not so low as fluor-spar. *Colour*—Colourless, with grey-blue dusky centre; or blue throughout; or clear blue towards margin and colourless within. *D. Refr.*—Isotropic; but occasional anomalies, as in leucite, the colours being very low greys.

Note.—See Nosean. LAPIS-LAZULI appears to be an allied species.

Hornblende. *Comp.*—$m\,(Mg, Ca, Fe)\,Si\,O_3 + n\,(Mg, Ca, Fe)\,(Al_2, Fe_2)\,Si\,O_6$ (for constitution, see Groth, *Tab. Uebersicht*, 1898, p. 151). Closely comparable to the monoclinic pyroxenes. *Syst.*—Monoclinic.

I. Like augite, but prisms often longer, and of more fibrous aspect. Tends to form in radial bunches in fissures and on joint-surfaces. Common in minutely fibrous and actinolitic forms as a product of paramorphism from pyroxene.

SMARAGDITE, which is thus produced, is a bright green, as seen in some gabbros. On many rock-surfaces the form of the cross-sections of the prism (see below) can be clearly seen.

II. *Form*—Prismatic, commonly with six-sided cross-sections, the bounding planes being the prism and the clinopinacoids. Prism-angle about 124°, the rhombus thus formed being cut off at its acute angles by the traces of the clinopinacoids. Often minute fibrous groups and veins occur. Surrounds altering pyroxenes, and often occurs as patches in them. *Cleav.*—Prismatic; in cross-sections the cleavages commonly show very clearly, the obliquity of their angle contrasting with the rectangular cleavages of the pyroxenes (figs. 26, 35). *Encl.*—Being itself so often a product of alteration, does not pass into schillerised types such as are prevalent among pyroxenes. *Zon.*—Somewhat rare; a dark zone of alteration sometimes appears at edge, where the crystal

has been acted on by a hot matrix, separation of magnetite having taken place. *Refr. Index*—About 1·65; thus shows pitted surfaces. *Colour*—Pale yellowish to strong brown (varieties with much ferric oxide); or pale green to dark bluish-green. SMARAGDITE is often almost or completely colourless in section; in thicker sections, a clear grass-green. The face-pleochroism of hornblende causes sections parallel to the principal axis to be of a distinctly darker colour than the cross-sections. *Pleo.*—Very marked in the coloured varieties, the axis-colours giving yellow-brown to deep brown or almost black, and pale yellow-green to strong dark green. In vertical sections the maximum coloration occurs when the shorter diagonal of the nicol is parallel to the principal axis. Compare tourmaline and biotite. *D. Refr.*—Fairly strong; colours like augite. Optic axial plane is the clinopinacoid. *Extinct.*—On clinopinacoid sometimes almost "straight;" angle with principal axis commonly about 10° or 12°, rising to 22°. Hence in random prismatic sections typically a small angle, as opposed to that of augite. The longer direction in prismatic sections is practically parallel to the slowest-ray vibration-trace. *Twins*—Fairly common, mostly simple; composition-face parallel to the orthopinacoid. The pleochroism makes their detection easy by means of the single nicol only, the two halves appearing differently tinted.

Note.—The cleavages in cross-sections form a safe means of distinguishing the amphiboles from the pyroxenes; the pleochroism is also commonly an excellent guide, but it must be remembered that pale hornblendes cannot be strongly pleochroic, while soda-pyroxenes are so in a fair degree. Note also the common form of the cross-sections. The destructive action of the magma, referred to above under "Zoning," often leaves only black and opaque skeletons of the hornblende crystals (compare Biotite). For allied amphiboles see actinolite, soda-amphibole, and tremolite. Also anthophyllite.

Hypersthene (see Rhombic Pyroxenes).

Ilmenite (see Titanic Iron Ore).

IRON.—Native iron is of very rare occurrence except in meteorites. It may be micro-chemically treated by placing a drop of acid solution of cupric sulphate on a grain or section; if native iron is present, copper will be at once deposited. It also decomposes the solution of ammonium molybdate used for detection of phosphates, a fine blue precipitate being formed, which does not occur when iron oxides are examined. Metallic iron is whiter and more lustrous than magnetite when viewed with reflected light under the microscope. Opaque in transmitted light.

Iron Pyrites. *Comp.*—FeS_2. *Syst.*—Pyrite is cubic (the easily decomposing MARCASITE is rhombic).

I. The cubic form is commonly recognisable with the eye or

lens; the hardness (= 6·5) distinguishes it from pyrrhotine (4) and copper pyrites (3·5). The colour is also whiter and more brassy.

II. *Form*—Mostly squares. *Colour*—Opaque by transmitted light; shows a brass-yellow colour, almost silvery-yellow, by reflected light. Easily thus distinguished from magnetite. Sometimes decomposed to opaque brown or brownish-white pseudomorphs.

Kaolin. *Comp.*—$H_4 Al_2 Si_2 O_9$ *Syst.*—Monoclinic or triclinic.

I. The soft white decomposition-product of felspars, often found as a powder between the crystals of granitoid rocks or in the matrix of elvans, &c.

II. *Form*—Occasionally shows well-defined hexagonal plates. *Colour*—Colourless. The powdery products occurring in sections of felspars appear opaque white by reflected light. *D. Refr.*—Being extremely thin, the little plates may give low colours, though the double refraction is in reality strong. *Extinct.*—Basal plates are not isotropic; they have been said to extinguish parallel to lines which are not perpendicular to any of the bounding edges.

KYANITE. *Comp.*—$Al_2 Si O_5$. *Syst.*—Triclinic.

I. Known by its beautiful blue colour and easy macropinacoidal cleavage, the mineral becoming truly lath-shaped on fracture. Sometimes in little blue granules, the colour being more delicate than that of haüyne. Found in some rocks of metamorphic origin.

II. *Form*—Often granular. *Cleav.*—Distinct. *Refr. Index*—High; slightly above olivine. *Colour*—Colourless, but blue in thick sections. *D. Refr.*—Between felspars and augite.

Labradorite (see Plagioclases).

Leucite. *Comp.*—$(K, Na) Al Si_2 O_6$. *Syst.*—Probably cubic

I. Small or large opaque white spheroidal crystals (icositetrahedra more or less rounded by external action). The small ones appear dull white throughout, but the larger show on fracture a translucent interior with almost a gummy lustre. Hardness very little below that of felspars. At present known almost exclusively in lavas.

II. *Form*—Octagonal or almost circular sections; several often grouped together. *Cleav.*—Not visible. *Encl.*—Foreign bodies, such as glass-enclosures, are often grouped regularly in zones or radially, forming sometimes a considerable part of the bulk of the crystal. The smaller leucites in the groundmass of lavas seem particularly to affect this habit. *Zon.*—As above stated, marked by enclosures. *Refr. Index*—1·508, and thus below that of the balsam. *Colour*—Colourless, but becoming earthy brown where decomposed. *D. Refr.*—The smaller crystals are commonly

isotropic; but the larger show a complex system of lamellæ crossing one another and light or dark grey in colour. In very thick sections (say 2 or 3 mm.) these lamellæ appear brilliantly coloured, like thick glass under stress. (Figs. 37, 40.)

Note.—Infusible, gives strong potassium flame-reaction (p. 85), and does not gelatinise in HCl. Compare Analcime.

LEUCOXENE (see Titanic Iron Ore).

Limonite. *Comp.*—$H_6Fe_4O_9$. A common earthy brown product of the alteration of ferriferous minerals. Orange-brown stains around sections of such minerals in altered rocks may be attributed to limonite. Seen commonly as a cementing material in sandstones. Yellowish-brown by reflected light.

Magnetite. *Comp.*—Fe_3O_4. *Syst.*—Cubic.

I. Iron-black grains or octahedra, with lustrous fracture-surfaces. Not scratched by knife. Well developed in some chlorite-schists.

II. *Form*—Sections of octahedra (squares and hexagons), or mere grains and patches. In the glassy groundmass of rocks forms skeleton-crystals of cross-like patterns, or rods and strings of united crystallites. Occurs also as a product of the decomposition of minerals, when iron is left behind after the removal of other bases. Thus the cracks of olivine are often marked out by magnetite (fig. 31), and the hornblendes of some lavas become dissolved away, leaving a skeletal pseudomorph of magnetite granules. *Colour*—Opaque even in thinnest sections; steel grey by reflected light.

Note.—Compare Chromite, Iron pyrites, and Titanic iron ore.

MELILITE (see p. 262).

Micas.—The members of this important group that are most frequently met with have so many characters in common that these are treated together here. *Comp.*—Two broad chemical groups may be formed, the alkali micas and the magnesium-iron micas; writing the bases in descending order of importance, the micas of the latter group are silicates of magnesia, alumina, iron, and alkalies, while those of the former are silicates of alumina, alkalies, iron, and magnesia. *Syst.*—Probably all are monoclinic.

I. The micas appear as lustrous little plates, silvery, bronze-coloured, green, or black, with a most exceptionally good basal cleavage. The knife scratches them easily, producing a very characteristic grating sound, audible even when minute flakes are operated on. The thumb-nail scratches them with difficulty, if at all (compare chlorite). Viewed from the side, the cleavage gives them a lamellar appearance and the characteristic lustre is lost.

II. *Form*—Hexagonal basal sections, often mere platy areas

with ragged edges. The lamellar character can commonly be seen by examining the margin of such sections with a ½- or ¼-inch power. Vertical sections are rectangular; but commonly the traces of the prism planes are lost, the edges of the cleavage-planes giving a ragged fibrous boundary, and the traces of the basal planes being on the contrary very sharp. Often bent and deformed among the other more resisting minerals. *Cleav.*—Basal, exceedingly well marked. *Encl.*—Dark patches often appear; some may be true enclosures, while others are developed around colourless enclosures of zircon, &c. *Zon.*—Coloured zones sometimes (but rarely) visible in basal sections. *Refr. Index*—Higher than quartz (= about 1·58). *Colour*—Colourless to brown and green. Darkest in basal sections. Decompose to green chloritic products. *Pleo.*—Very strong in coloured varieties. Darkest tints occur when the cleavage-lines are parallel to the shorter diagonal of the nicol. *D. Refr.*—Exceptionally strong (about ·04), being higher than common epidote. The optic axial plane is parallel to the clinopinacoid or the orthopinacoid; the basal sections (or, better still, cleavage-flakes taken from the rock-specimen direct) show admirable figures with convergent light, the optic axial angle being 0° to about 70°. *Extinct.*—Vertical sections extinguish perpendicular and parallel to the basal cleavage, the minute deviations from this rule not being recognisable in rock-sections. *Opt. Sign*—Negative; the principal axis is practically the vibration-direction for the fastest ray, the deviation of the acute bisectrix from it being inappreciable.

Note.—See Biotite, Muscovite, and Phlogopite. In cases of doubt it is best to speak merely of "dark mica" or "light mica" until better tests can be applied.

MICROCLINE and SODA-MICROCLINE (ANORTHOCLASE).—*Comp.*—Like orthoclase and soda-orthoclase. *Syst.*—Triclinic; pseudo-monoclinic.

I. The common felspar of graphic granite. On its surfaces the lens generally reveals a structure of opaque little whitish rods crossing at right angles and alternating with somewhat more translucent areas. Flesh-red, yellowish, or green (Amazon-stone). G = 2·57, to 2·60 in soda-microcline.

II. Resembles orthoclase, but shows with crossed nicols a more or less defined system of repeated twinning, the minute lamellar components crossing one another nearly at right angles and producing a coloured mesh-work.* As Rosenbusch shows,

* Sabersky's ingenious explanation of this effect (*Neues Jahrb. für Min.*, Beilage Bd. vii., 1891, p. 360), as due to the crossing of the lamellæ of only one set of twin-components, those of the albite type, is difficult to verify, but must clearly be taken into consideration.

if one group be set upright in the field, and rotated until extinction occurs in one of the sets of lamellæ composing it, one set from the group lying perpendicular to the first is, in most sections, simultaneously extinguished. Black bands crossing one another at right angles are thus conspicuous in the field. In the zone parallel to the microdiagonal, the maximum angle of extinction for the albite-type of lamellæ is 18°.

In basal cleavage-plates, extinction occurs at 15½° from the trace of the pinacoidal cleavage (at 0° in orthoclase). *Refr. Index*—1·526. (See Plagioclases, and fig. 25.)

Muscovite. *Comp.*—$H_2 K Al_3 Si_3 O_{12}$ (after *Groth*). A typical and common alumina-alkali mica. For general characters, see Micas. Special points:—

I. Commonly light-coloured and silvery, but approaching black as the crystals become thicker. Very common in mica-schists (often with SERICITE and other varieties); also in many granites.

II. *Colour*—Colourless or palest yellow-brown. *Pleo.*—Visible if the mica shows even a trace of colour. *D. Refr.*—Strong (·041). Colours commonly pinks and greens of third and fourth orders, or high white. Sections parallel to the basal cleavage are not, as in typical biotite, practically isotropic. This point may be conveniently observed in cleavage-flakes. Optic axial angle wide (50° to 70°), the figure with convergent light being a striking one and easily obtained with fairly thick cleavage-plates. Optic axial plane perpendicular to clinopinacoid. The trace of the optic axial plane, which is easily found by the axial figure, is the vibration-direction of the slow ray in the cleavage-flake. (Figs. 24 and 43.)

Note.—Often occurs in minute forms in altered potash-felspar. SERICITE is covered by the above description. See Micas, Biotite, and Phlogopite.

NATROLITE. *Comp.*—$Na_2Al_2Si_3O_{10} + 2H_2O$. *Syst.*—Rhombic.

I. A common product of the decomposition of such silicates as nepheline, soda-felspars, &c. Occurs in radiating fibrous groups, colourless or stained light brown. Hardness = 5·5, but difficult to test in the rock, owing to the brittle nature of the prismatic crystals. See Blowpipe characters, p. 74.

II. *Form*—Like most zeolites, forms radiating groups of prisms in decomposing minerals or in cavities of the rock. *Refr. Index*—1·483; below that of felspars. *Colour*—Colourless. *D. Refr.*—Commonly bright first order colours. The fibrous groups naturally show a partial or complete dark cross with crossed nicols (see p. 149). *Extinct*—Rhombic. *Opt. Sign*—Positive; the longer direction of the prism is that of vibration for the slowest ray.

Nepheline. *Comp.*—Approximately (Na, K) Al Si O_4. (See p. 74.) *Syst.*—Hexagonal.

I. Brown or greenish greasy-looking masses in holocrystalline rocks (ELÆOLITE), or colourless grains and short hexagonal prisms in lavas. Excellently seen thus in the latter form in the well-known basalt of Katzenbuckel, Odenwald, where it plays the part of a porphyritic felspar. Hardness = 5·5; thus just scratched with a knife when fresh.

Very easily decomposed, and then produces soft grey-brown areas and pseudomorphs, in which recrystallisation is going on, resulting in zeolites. On some phonolites the little hexagonal cross-sections of nepheline can be picked out with the eye as opaque lighter patches in a grey or brownish groundmass.

II. *Form*—Irregular grains (ELÆOLITE) or short hexagonal prisms, giving squares and hexagons as the most typical sections. *Cleav.*—Not seen. *Encl.*—Common, arranged in zones. *Zon.*—Common. *Refr. Index*—1·543. *Colour*—Colourless. When decomposed, a very characteristic earthy yellowish-brown. *D. Refr.*—Colours like apatite; lower than felspars. Hexagonal sections isotropic, unless oblique. When altered, gives fibrous aggregate effect. *Opt. Sign*—Negative. (Fig. 34.)

Note.—Compare apatite and nosean. See also analcime and natrolite for decomposition-products. In the elæolite-syenites the weaker double-refraction helps to distinguish the elæolite from the untwinned felspars, while convergent light of course gives a uniaxial figure.

NOSEAN. *Comp.*—$Na_5 Al_3 Si_3 O_{12} . S O_4$ (= $Na_3 Al_3 Si_3 O_{12}$ + $Na_2 S O_4$). *Syst.*—Cubic.

I. Often visible as dark grey hexagonal sections on the rock-surface. Forms thus darker patches in the grey or brown groundmass of some phonolites; sometimes opaque light brown.

II. Like haüyne, but commonly larger, and colourless to greyish-brown. Dark outer zone often conspicuous (as in the fine corroded examples in the leucitite of Rieden, Eifel, seen in fig. 37).

Note.—See Haüyne. Nosean or haüyne can be treated microchemically by decomposing with dilute hydrochloric acid and evaporating at a merely moderate temperature. If crystals of gypsum are formed abundantly (commonly in radiating bunches) the mineral is haüyne.

Oligoclase (see Plagioclases).

Olivine. *Comp.*—$(Mg, Fe)_2 Si O_4$. *Syst.*—Rhombic.

I. Granules or approximately rectangular crystals, somewhat conspicuously marked out by their yellow-green colour and glassy lustre from their surroundings, which are commonly darker silicates. Not scratched by the knife. Sometimes, with chromite, builds up considerable rock-masses. Diopside may be mistaken at times for olivine. When altered, however, the

appearance of olivine changes greatly. It becomes soft and grey-green, or even black if much magnetite has separated out within it. Thus in the "Forellenstein" (Troctolite) of Volpersdorf or the Lizard, and in many rocks with "lustre-mottling" (see p. 101), the mineral appears as dusky grey-black granules, and might be mistaken in some gabbros for a decomposing pyroxene. It is very important to bear in mind this masking of olivine by its decomposition-products (fig. 31).

II. *Form*—Rarely a perfect outline, but typically an elongated hexagon; in many lavas and in rocks with granitic structure, irregular forms or elliptical grains; also common as groups of grains. Very often cracked and corroded in lavas, since it occurs as a porphyritic constituent. *Cleav.*—Not often visible. *Encl.*—Liquid and other enclosures common, often in delicate ramifying forms. Schillerisation may be studied in all stages in olivine, some sections finally looking almost diallagic (as in the dolerite of Kentallen, Appin). *Refr. Index*—1·679; near the pyroxenes. *Colour*—Colourless. Faint yellow-brown in the exceptionally ferriferous varieties. Alteration-products green of various shades, occurring on margin and along cracks (fig. 38), often with development of opaque granules (magnetite). *Pleo.*—The green decomposition-products are pleochroic. *D. Refr.*—As strong as epidote; weaker than muscovite. *Extinct.*—Parallel to the axes of symmetry of most of the sections.

Note.—Frequently only to be traced as pseudomorphs (see Serpentine). Calcite may thus replace olivine. Prof. Judd has shown that many patches of magnetite may represent altered olivine. MM. Lévy and Lacroix describe a transparent red decomposition-product with distinct macropinacoidal cleavage. Note the colourless character of unaltered olivine.

Opal. *Comp.*—$Si\,O_2$; perhaps some water. *Syst.*—Amorphous.

I. Opalescent, appearing bluish by reflected and brownish by transmitted light. Sometimes clear and colourless (hyalite). Occurs with chalcedony, commonly in cavities of rhyolitic or trachytic lavas; also replacing wood. Hardness sometimes below 6.

II. In sections colourless, sometimes showing iridescent films by reflected light. Isotropic, with occasional strain-phenomena, producing a black cross between crossed nicols. See Chalcedony.

Orthoclase. *Comp.*—$(K, Na)\,Al\,Si_3\,O_8$. *Syst.*—Monoclinic, or pseudo-monoclinic.

I. Prismatic or granular. Clear and colourless, with faint brownish exterior and vitreous lustre (SANIDINE of lavas) to nearly opaque white, grey, brown, or red crystals (common orthoclase). Occasional schillerised and iridescent forms.

Cleavage-planes well marked, basal and clinopinacoidal, with vitreous to pearly lustre. Hardness = 6. G = 2·56-2·58. Strong potassium reaction in flame. Twin forms very often recognisable. Where the outer form is obscure, as in most granites, the fractured surface of the rock shows crystals with the basal cleavages sloping in one half towards the eye and in the other and duller half away from it, giving thus evidence of the simple twinning (p. 16).

II. *Form*—Prismatic; cross-sections approximately rectangular. Rarely truly granular, and thus differing from quartz. *Cleav.*—Distinct, often in both principal directions, and marked by dusky decomposition-products. Not ordinarily seen in SANIDINE, which shows rudely parallel cracks. *Encl.*—Common. Frequently schillerised. *Zon.*—Zones fairly common. *Refr. Index*—1·523. Little below quartz, and thus close to that of the balsam. *Colour*—Colourless, with dusky grey decomposition-products (fig. 26); white mica is very common among these. SANIDINE is as clear and colourless as quartz (fig. 33). *D. Refr.*—Weak (·007); colours grey in thin sections; brighter tints of first order in many ordinary sections. Optic axial plane either the clinopinacoid or perpendicular to it, the latter case being by far the most common. The plane is then almost parallel to the base. *Extinct.*—Straight in sections from the orthodiagonal zone, and occurring at 21° from the vertical axis in the clinopinacoid, the measurement being made towards the obtuse angle formed by the traces of the base and orthopinacoid. The basal cleavage-flake extinguishes straight with the trace of the clinopinacoidal cleavage, and the clinopinacoidal flake at 5° from the basal cleavage. *Twins*—Simple twinning common, though sections may easily pass through one half only. Plane of composition often step-like or irregular. A squarish section with the composition-plane running diagonally is almost sure to be from a Baveno twin.

Note.—SODA-ORTHOCLASE cannot be divided off satisfactorily from common orthoclase, as far, at any rate, as rock-forming types are concerned.

Distinguish clear orthoclase from quartz by outline, cleavages, zoning, oblique extinction in most prismatic sections, and twinning. Where decomposition has set in, remember that quartz shows no such products. Distinguish orthoclases from plagioclases by presence of repeated twinning in most crystals of the latter. See Microcline and Plagioclases.

OTTRELITE and CHLORITOID. *Comp.*—$H_2(Fe, Mg, Mn)Al_2SiO_7$. *Syst.*—Monoclinic (perhaps triclinic).

I. Characteristic iron-black or black-green lozenge-shaped or oval plates in some metamorphic rocks. Hardness above 5; hence sharply distinct from chlorites.

II. Distinct basal cleavage. Greenish-blue colour; the central portion is sometimes darker and shaped like an hour-glass, a lighter area appearing on each side. Marked pleochroism.

Note.—Ottrelite is well observed in the schist of Ottrez in the south-east of Belgium. Some uncertainty hangs over the relations of ottrelite and the more widely distributed chloritoid. If a chemical difference really exists, ottrelite proper contains manganese as well as magnesia, while chloritoid does not.

PHLOGOPITE.—A mica of the ferro-magnesian type, with little iron. For all general characters see micas. Special points:—

I. Typically bronze-coloured rather than black.

II. *Colour*—Colourless when thin. *D. Refr.*—Basal sections deviate from isotropism more than those of biotite, the optic axial angle being typically larger. But some show merely a black cross during rotation above convergent polarised light.

Note.—See Micas, Muscovite, and Biotite.

PINITE.—An earthy grey pseudomorphous replacement of cordierite and other silicates, being itself a hydrous silicate of alumina and potash with some little magnesia, iron oxide, and soda. Produces grey patches in the rock-mass, or sometimes, as in eurites of Auvergne, well bounded prismatic pseudomorphs. Under the microscope gives fibrous tufts and irregular cloudy patches.

Plagioclases.—This great group of felspars forms too continuous a series to allow of the separate discussion of its members. *Comp.*—Silicates of alumina, potash, soda, and lime; the group includes:—

Microcline and **Soda-microcline.** $(K, Na) Al Si_3 O_8$. (See p. 168.)
Albite. $Na Al Si_3 O_8 = Ab$.
Oligoclase.* $Ab_3 An_1$ to $Ab_2 An_1$.
Andesine. $Ab_2 An_1$ to $Ab_1 An_1$.
Labradorite. $Ab_1 An_1$ to $Ab_1 An_3$.
Bytownite. $Ab_1 An_3$ to $Ab_1 An_6$.
Anorthite. $Ca Al_2 Si_2 O_8 = An$.

Syst.—Triclinic; closely comparable in type to orthoclase, the brachypinacoid corresponding to the clinopinacoid in the latter.

I. Commonly prismatic, but may be minutely so or granular. Colourless and glassy to opaque white. Sometimes a delicate blue-grey; rarely red. Schillerised and iridescent forms occa-

* The plagioclases between albite and anorthite are commonly regarded as built up of molecules of these two felspars in varying proportions; hence oligoclase becomes $n\, Na Al Si_3 O_8 + Ca Al_2 Si_2 O_8$, and labradorite $Na Al Si_3 O_8 + n\, Ca Al_2 Si_2 O_8$. The proportions here given are those adopted by Hintze, following Tschermak.

sionally seen when the mineral is coarsely developed; but also known in soda-orthoclase. Basal and brachypinacoidal cleavage-planes easily seen, particularly the former. Hardness = 6. Specific gravity rises as follows:—**Albite**, 2·62-2·64; **oligoclase**, 2·64-2·66; **andesine**, 2·66-2·69; **labradorite**, 2·69-2·71; **bytownite**, 2·71-2·74; **anorthite** 2·74-2·76. (Hintze, *Mineralogie*, Bd. ii., p. 1431). Twin-forms show to the eye or lens alternately reflecting or duller lamellæ, according to the position of the surface of fracture with regard to the cleavages in the individual lamellæ. A number of fine lighter or duller bands is thus often visible, especially with the lens, parallel to the longer direction of the prismatic form (p. 16).

Albite is often found filling up cracks or crystallised in cavities as a mineral of secondary origin.

II. *Form*—Prismatic; cross-sections approximately rectangular. In many rocks granular, especially when developed as secondary products. Often greatly corroded, the glassy matrix penetrating throughout the crystal along cleavage or solution-planes (fig. 38). *Cleav.*—Sharp in the coarser forms; often in these marked out by dusky decomposition-products. *Encl.*—Common. Frequently schillerised, the felspars of many gabbros showing this character excellently. *Zon.*—Zones common, frequently giving different colours and extinctions with crossed nicols, owing probably to the crystal being built up of isomorphous felspars successively developed from the matrix. *Refr. Index*—Always near that of the balsam. The average indices are:—**albite**, 1·535; **oligoclase**, 1·540; **andesine**, 1·553; **labradorite**, 1·558; **bytownite**, 1·569; **anorthite**, 1·580. All sections of microcline and anorthoclase, and almost all sections of albite and oligoclase rich in soda, have a refractive index below that of ordinary balsam; basic oligoclase and all the remaining plagioclases have an index above that of the balsam in all sections. *Colour*—Colourless, with dusky grey decomposition-products. The interior is often thus clouded while the outermost zones are clear. Sometimes the whole crystal is reduced to calcite and epidote. *D. Refr.*—Weak (·008), rising to ·013 in **anorthite**. The colours are greys or slightly higher tints of the first order. *Extinct.*—These may be sometimes studied on cleavage-flakes. The extinctions have thus been worked out for sections parallel to the base and to the brachypinacoid. Hap-hazard sections in ordinary slides, particularly when repeatedly twinned, present many difficulties of determination. In reading basal cleavage-plates, the trace of the brachypinacoid shown by the other cleavage, or by the common albite-type of twinning, is set upright in the field, and the

extinction-angle is measured from this guide-line. We may note that, while oligoclase has in such sections nearly straight extinction, albite and labradorite give angles of 5° and 9° respectively, on opposite sides of the guide-line if the plates examined are kept each in the same position with regard to the crystals from which they were broken. Anorthite, on the other hand, has a high angle, as much as 37°, which is very distinctive, its ally bytownite giving only 17½°.

If a brachypinacoidal cleavage-flake is so placed that the trace of the basal cleavage is upright in the field, while the obtuse angles formed by this and the direction of the vertical axis lie below on the left and above on the right, then the extinction will occur after the following amounts of rotation of the crystal:—

Albite, ...	20°	to the left.
Oligoclase, ...	5°	,, ,,
Labradorite, ...	24°	,, right.
Anorthite, ...	37°	,, ,,

On comparing these figures with those for the basal flakes, we see that if we break a cleavage-flake hap-hazard from a felspar, not knowing what species or which cleavage we are dealing with, and set the trace of the other cleavage upright in the field, we have the last given series of figures as maximum angles of extinction for the principal species. As before, the angle referred to is that between the trace of the cleavage and the direction of extinction that lies nearest to it; but the rotation may be to one hand or the other. We may, however, on determining the angle in the unknown cleavage-plate first obtained, then seek to procure a plate from the second cleavage-surfaces of the specimen. A comparison of the results obtained with both plates will be of service. Thus, while the distinction between labradorite and albite will still be difficult, oligoclase will give a low (1° to 5°) and anorthite a high angle (37°) in both flakes.

MM. Lévy and Lacroix show how the extinctions of the triclinic felspars may be utilised in the case of microscopic sections. Thus, in particular, a section is sought for in which lamellar twinning of the albite type is distinct, and in which extinction of the alternate sets of lamellæ takes place at the same angle on opposite sides of the trace of the plane of composition, which is used as a guide-line. The two sets of lamellæ will thus show equal degrees of illumination in the upright position in the field, a fact that is of great assistance in the selection of sections for measurement. Such a section, which is not always easily found in a single slide, has been cut parallel to the axis of rotation of the twin-lamellæ

of the albite type—*i.e.*, to a line perpendicular to the brachypinacoid. The lamellæ of the pericline type will also be extinguished symmetrically in sections from this zone. Sections showing this symmetrical extinction and yielding *low* angles are approximately parallel to the basal plane; those giving *high* angles should be selected. The maximum extinction-angles of the albite type of lamellæ in faces from this zone are as follows:—*

Albite, ...	16°
Oligoclase, ...	5°
Andesine, ...	16° (basic varieties 22°).
Labradorite, ...	27° (basic varieties 38°).
Bytownite, ...	45°
Anorthite, ...	53°

Were it possible to determine how each section has been cut, even albite and andesine could be distinguished from a difference in the direction of rotation; but Becke's simple method for the observation of relative refractive index effects this admirably, whenever sections of the felspar can be found abutting on the balsam at the edge of the slide (p. 142). *Twins*—Repeated twinning is extremely common, the lamellæ being often very numerous. Both the albite type, with the brachypinacoid as the twin-plane and composition-plane, and the pericline type, with the "rhombic section" as the composition-plane and practically the same axis of rotation as the former type, may occur in the same crystal, giving cross-twinning coarser than the typical microcline structure. In sections from the zone of the base and macropinacoid the traces of the lamellæ of the two systems are almost at right angles. Other types of twinning occasionally occur; the Carlsbad type is indeed common, one half showing, in addition, numerous lamellæ of the albite type, while the other shows few or no lamellæ. See Microcline.

Note.—Distinguished in general from orthoclase in ordinary sections by this character of repeated twinning. The discrimination of one plagioclase from another is a matter requiring considerable care, and the methods should be further studied in the larger text-books. A series of trials with Szabó's system of flame-reactions (p. 84) will often help when the mineral has been proved to be a plagioclase, and specific gravity tests with dense liquids are of great service.

The dull white altered felspars, full of recrystallised decomposition-products (mainly members of the zoisite group or garnet), that are common in many older diorites and gabbros,

* Lévy, *Détermination des Feldspaths*, 1894, p. 31.

were formerly known as SAUSSURITE. Such forms may be termed "saussuritic felspars" (fig. 45).

Pyrite (see Iron Pyrites).

PYRRHOTINE. *Comp.*—$F_7 S_8$, or $Fe S$ (?). *Syst.*—Hexagonal. Rather redder than iron pyrites. Hardness = about 4, the particles cut out being easily attracted by the magnet. Opaque granular in sections.

Pyroxenes (see Augite, Diopside, Rhombic Pyroxenes, and Soda-pyroxenes. Also Bastite).

Quartz. *Comp.*—$Si O_2$. *Syst.*—Hexagonal (Trigonal).

I. Commonly clear and colourless, with vitreous lustre. No cleavage; conchoidal fracture, thus resembling glass. Unscratched by knife. Grains (which should be looked for with the lens); short prism and two rhombohedra (in some eurites); or longer prisms terminated by rhombohedra (when formed in cavities or in sedimentary rocks). Occurs also filling veins, and is often in such cases almost opaque white.

II. *Form*—In igneous rocks seldom shows crystal-outline. Commonly allotriomorphic or in corroded grains (fig. 32), but well bounded in some eurites. Micropegmatitic intergrowths with duller felspar may be expected. In metamorphic and in many plutonic rocks quartz forms aggregates of little granules, which are well revealed by the polariscope. Commonly cracked irregularly. In veins, and in residues of limestones, &c., shows good crystallographic outlines. *Cleav.*—None. *Encl.*—Liquid-enclosures with moving bubbles commonly very abundant in the quartz of deep-seated or metamorphosed rocks, the lines along which they have developed often passing continuously across several grains (see fig. 19). These irregular strings and patches of minute enclosures may be taken for dull decomposition-products, such as kaolin, unless a high power is used. Glass-enclosures with fixed bubbles, and sometimes with the form of negative crystals, occur in the quartz of many lavas. *Zon.*—Exceedingly rare, except in crystals of sedimentary origin. *Refr. Index*—1·547, almost exactly that of the balsam. *Colour*—Colourless. See, however, Amethyst. No decomposition-products. *Pleo.*—Observable in the exceptional coloured varieties, which have little claim to be called rock-forming minerals. *D. Refr.*—Weak (·009); like the felspars. The absence of decomposition, as compared with other minerals in the slide, is often brought out by the clear colours given by quartz between crossed nicols. Thin basal sections show in convergent light the ordinary black cross, the characteristic coloured central area, due to rotatory polarisation, being visible only in specially

cut thicker sections. *Opt. Sign*—Positive. *Twins*—None in rock-sections.

Note.—Compare and carefully contrast with orthoclase and plagioclases. See also Chalcedony, Opal, and Tridymite, and figs. 24 and 25.

Rhombic Pyroxenes. *Comp.*—(Mg, Fe) Si O_3. The rock-forming examples of these were long confused with monoclinic pyroxenes, which they generally resemble to the eye. The boldly developed lustrous types familiar to mineralogists, such as the bronzite of the Kupferberg and the hypersthene of Paul's Island, Labrador, may now be regarded as altered forms of minerals possessing no such lustre. Hence Tschermak proposes for the rhombic pyroxenes a purely chemical grouping:—

Enstatite;	Fe O = less than 5°/。.
Bronzite;	„ = 5 to 15°/。.
Hypersthene; . . .	„ = 15°/。 and upwards.

To these Prof. Judd,* reviving an older name of vom Rath, adds AMBLYSTEGITE; Fe O = 25 to 35%.

I. Commonly closely resembling augite; sometimes as pale as diopside. The schillerised forms, bronzite and hypersthene of older authors, occur in some holocrystalline rocks. Monoclinic pyroxenes with similar lustres were also formerly classed under these names.

II. *Form*—Nearly isomorphous with monoclinic pyroxenes; hence the frequent confusion with them. Prism-angle 88°. Habit and sections similar to augite (fig. 36). *Cleav.*—Prismatic, thus also intersecting nearly at right angles. *Encl.*—Schillerised forms fairly common, but not to be expected in more modern lavas. *Refr. Index*—1·66–1·70. *Colour*—Like monoclinic pyroxenes; colourless, yellowish-brown, at times greenish. **Hypersthene** and AMBLYSTEGITE, owing to the striking pleochroism, often appear greenish or pink-red in the same slide. Decompose to green products. See Bastite. *Pleo.*—**Enstatite** is too pale to exhibit pleochroism; **bronzite** and the more ferriferous members of the series show bluish-green when the shorter diagonal of the nicol is parallel to the vertical axis, brown when it is parallel to the macrodiagonal, and a fine red-brown, when it is parallel to the brachydiagonal. This effect is naturally very striking in AMBLYSTEGITE. *D. Refr.*—Somewhat weaker than in the monoclinic pyroxenes, and even approaching quartz in the case of **enstatite**. Optic axial plane is the brachypinacoid.

* *Geol. Mag.*, 1895, p. 173. Also *Quart. Journ. Geol. Soc.*, vol. xli., (1885), p. 371.

Extinct.—Rhombic; thus markedly distinct from the monoclinic pyroxenes, with the exception of those extremely rich in soda. The direction of the vertical axis is that of vibration for the slowest ray.

Note.—Intergrowths with diallage have been observed, the brachypinacoid of the rhombic form being applied to the clinopinacoid of the monoclinic. Distinguish the rhombic pyroxenes by the straight extinction and, if possible, by the pleochroism. In some remarkable granular rocks the pink rounded sections of hypersthene resemble in ordinary light the garnets occurring in the same slide. The nicols at once prove the latter to be isotropic.

In the absence of microscopic sections, rocks must often be called "pyroxene-andesite," "pyroxene-diorite," &c., until accurate determination can be made.

Compare carefully with diopside, augite, and soda-pyroxenes.

For altered forms see Bastite and Serpentine.

RIEBECKITE (see Soda-Amphiboles).

RUTILE. *Comp.*—TiO_2. *Syst.*—Tetragonal.

I. As a rock-forming constituent rutile is generally invisible until the microscope is applied. May appear as hard rich brown or black specks. Its high specific gravity (4·2) makes it separable by dense liquids.

II. *Form*—Granules and aggregates, with sometimes distinct prismatic forms. Minutely distributed in the altered minerals of some gabbros; also in practically all argillaceous and chloritic metamorphic rocks, and also in clays. Shows typically minute geniculated twins, sometimes heart-shaped. *Refr. Index*—Extremely high (= 2·712). The tiny crystals and grains thus stand out with strongly marked margins. *Colour*—Yellow-brown to red-brown. Lustrous black by reflected light. *Twins*—As above stated; highly characteristic.

SANIDINE (see Orthoclase).

SAUSSURITE (see paragraph at end of Plagioclases).

SCAPOLITES. *Comp.*—A series of minerals with meionite at one end and marialite at the other, being silicates of alumina, lime, and soda, with some chlorine, the lime preponderating largely over soda in the meionite molecule. *Syst.*—Tetragonal.

I. Crystallised in cavities of some lavas; also often occur associated with altered felspars, the products of which are recrystallising. Colourless to white or grey. Soluble in hydrochloric acid, leaving a residue of non-gelatinous silica.

II. In sections a number of clear colourless granules sometimes appears in the place of felspathic constituents. They are liable to be mistaken for secondary felspars or even quartz. *Form*—Commonly granular. *Cleav.*—Often not distinct. *Refr.*

Index—About 1·57. *Colour*—Colourless. *D. Refr.*—Considerably stronger than felspars in the highly calciferous varieties, being near olivine in the case of meionite. In DIPYRE, however (the common gra· ular type in holocrystalline rocks), the double refraction is fairly weak (= about ·014). Uniaxial figure in convergent light. *Opt. sign*—Negative.

Note.—For an account of the relations of the scapolites and plagioclases, and references to the literature of the subject, see Prof. Judd, "On the processes by which a plagioclase felspar is converted into a scapolite," *Min. Mag.*, vol. viii. (1889), p. 186.

SERICITE (see Muscovite).

Serpentine. *Comp.*—$H_4 (Mg, Fe)_3 Si_2 O_9$. *Syst.*—Rhombic.

I. Soft grey-green, green, black, or red areas among decomposing ferro-magnesian minerals, or even building up the mass of a rock. Hardness about 3. Sometimes crystallised in pale or golden-yellow fibres in veins running across the rock (chrysotile).

II. *Form*—Pseudomorphous, in patches, or in veins and cracks. Minute tufts and fibres often developed. Does not look so uniform as chloritic areas. The serpentine has often the ovoid form of olivine granules, the cracks of the latter being at times marked by bands of magnetite. *Refr. Index*—Low; close to that of the balsam. *Colour*—Yellow, yellow-green, or blue-green. Most commonly a yellowish-green. Colourless highly refracting areas of olivine are often left surrounded by the serpentine. *Pleo.*—Distinct, in shades of green. *D. Refr.*—Close to that of ordinary plagioclases. Shows tufts and fibres in polarised light, the serpentinous areas being made up of a number of needles. These needles, picked out between crossed nicols, frequently seem at or nearly at right angles to one another, and it is often stated that the serpentine in such cases has been derived from pyroxene; but the structure is extremely common in company with others which indicate with certainty olivine. It is probable that in some cases described the rectangular effect is due to the illusion referred to on p. 149. (Figs. 31 and 38.)

Siderite. *Comp.*—$Fe C O_3$. Resembles dolomite in sections, but is yellow-brown or greenish, with marked pleochroism. Sometimes occurs as oolitic grains (see p. 210).

SILLIMANITE. *Comp.*—$Al_2 Si O_5$. *Syst.*—Rhombic. Common in bunches of minute white prisms (colourless in sections) in schists altered by contact with granite. *D. Refr.*—·02.

Note.—Infusible, and gives good alumina reaction with cobalt nitrate. Minute fragments of rock may be thus treated and examined later under microscope.

SMARAGDITE (see Hornblende).

SODA-AMPHIBOLES. *Comp.*—All may be represented as $Na(Fe, Al)Si_2O_6$, with some $(Fe, Mg)SiO_3$. Like common hornblende in most respects. ARFVEDSONITE, with little alumina, cannot be distinguished from common hornblende by simple microscopic tests. The colour is brown or dark green.* Where the other minerals in the slide, such as nepheline, are rich in soda, the amphibole is likely to be arfvedsonite. GLAUCOPHANE, with little iron, gives a silky blue-black, inclining to slate-blue, appearance to the rock-surface. Its face-colours are pale violet-blue to greenish-blue or even yellowish. The darkest axis-colours occur when the longer axis of a prismatic section lies nearly parallel to the shorter diagonal of the nicol. The extinction-angle is only about 5° in clinopinacoidal sections; hence very small in most hap-hazard prismatic sections. The longer axis of the prisms nearly coincides with the direction of vibration for the slowest ray. In the ferriferous forms, arfvedsonite and riebeckite, this direction is that of vibration for the fastest ray. RIEBECKITE is blue in sections, with blue and green, or blue and dull straw-brown, axis-colours. Some amphiboles show secondary outgrowths of soda-amphibole.

Note.—In small prisms it is possible to mistake a blue soda-amphibole for a blue variety of tourmaline. But in the latter mineral the greatest absorption—*i.e.*, the darkest tint of the pleochroism—occurs when the shorter diagonal of the nicol is perpendicular to the longer axis of prismatic sections.

SODALITE. *Comp.*—$Na_4Al_3Si_3O_{12}Cl$. *Syst.*—Cubic.

I. Can be seen as small colourless cubes in the hollows of some trachytic lavas. Sometimes a fine blue.

II. *Form*—Sections of cube, suggesting at first vertical sections of nepheline. Sometimes in larger irregular grains. *Refr. Index*—Lower than that of the balsam (1·486). *Colour*—Colourless to faint blue. *D. Refr.*—None. Isotropic.

Soda-Orthoclase (see Orthoclase).

Soda-Pyroxenes. *Comp.*—Approaching $Na(Fe, Al)Si_2O_6$. ÆGIRINE and ACMITE are non-aluminous. The common green monoclinic pyroxenes of trachytic and andesitic rocks, as well as of some syenites and diorites, must be referred to merely as soda-pyroxene. They resemble augite, except in colour and their marked pleochroism; cross-sections are lighter in tint than vertical ones, the former being yellow-green and the latter darker green. The axis-colours are various tints of green. ACMITE

* Rosenbusch distinguishes arfvedsonite, green and optically positive, from barkevikite, which is brown and negative.

gives brown colours, ÆGIRINE green, and both have a smaller extinction-angle on the clinopinacoid (about 5°) than the common green rock-forming pyroxenes. The latter, being aluminous and monoclinic, are sometimes styled soda-augite.

Note.—Green pleochroic zones sometimes surround or occur within normal purple-brown augites. The longer axis of the prisms is near the vibration-direction for the fastest ray in soda-pyroxene, and near that for the slowest ray in amphibole.

SPHENE. *Comp.*—$Ca\ Si\ Ti\ O_5$. *Syst.*—Monoclinic.

I. Sometimes, as in syenites, visible on surface as yellow or brown-red pyramidal-looking crystals, small in comparison with the other constituents (see p. 76).

II. *Form*—Common section lozenge-shaped (a somewhat acute rhombus), the boundaries being traces of the pyramid planes. At times imperfect or partly rounded. *Cleav.*—Prismatic, and thus not parallel to the common outlines of the section; often seen in the larger examples. *Refr. Index*—Close to zircon (1·93); thus even higher than garnet. *Colour*—Pale pinkish or yellowish-brown, to darker yellow-brown. *Pleo.*—Slight. *D. Refr.*—Exceptionally strong, though not so strong as calcite. Pale colours of fourth or higher orders. *Twins*—Fairly common, composition-plane parallel to orthopinacoid. (Fig. 26.)

Note.—The lozenge-shape and high refractive index call attention to even small sphenes in rock-sections. For LEUCOXENE, which is referred to sphene, see Titanic Iron Ore.

SPINELLOIDS.—A name adopted for the isomorphous series of cubic minerals commencing with spinel ($Mg\ Al_2\ O_4$), including chrome-spinels and chromite, and terminating with magnetite ($Fe\ Fe_2\ O_4 = Fe_3\ O_4$). Their common characters are those of magnetite; but there is a greater degree of translucency as we pass through chromite to true spinel, the refractive index being always high. Chrome-spinel is brown-green or green in sections, which are, of course, isotropic. Common spinel cannot well be distinguished from garnet in sections (see p. 76 for Blowpipe-tests).

STILBITE (DESMINE). *Comp.*—$Ca\ Al_2\ Si_6\ O_{16} + 6\ H_2\ O$, with some Na_2 and K_2 replacing Ca. *Syst.*—Monoclinic.

I. A fairly common zeolite, occurring in groups of platy crystals in cavities of calciferous lavas. Occasionally in radial groups. White or red. Pearly lustre characteristic.

II. *Form*—Long prismatic sections. *Refr. Index*—Below that of felspars (1·497). *Colour*—Colourless. *D. Refr.*—Weaker than natrolite; pale first order colours. *Extinct.*—In clinopinacoid only

about 7° away from principal axis. Vibration-direction for fastest ray practically corresponds with longer direction of the prismatic sections.

TALC. *Comp.*—$H_2 Mg_3 Si_4 O_{12}$. *Syst.*—Rhombic.

I. Difficult to distinguish from white micas in small flakes, but less brilliant, and hardness = 1. Easily recognised in well-developed talc-schists.

II. Appears as greyish or colourless streaky areas formed of crystals with a basal cleavage. Strong double refraction.

Titanic Iron Ore. *Comp.*—Ilmenite = $m \, Ti Fe O_3 + n \, Fe_2 O_3$, and is hexagonal.

I. The rock-forming granules resemble magnetite.

II. *Form*—Hexagons and granules. *Colour*—Opaque; decomposition-products in part dusky-brown and translucent, and referred to sphene. Black by reflected light, with a white meshwork, or irregular patches, of decomposition-products. These, whether translucent or opaque, may be styled LEUCOXENE when they cannot with certainty be described as sphene.

Note.—Close associations of titanic iron ore and magnetite probably occur, and some magnetite may be titaniferous without containing intergrown with it any true hexagonal ilmenite. Hence the term titanic iron ore is used here to cover all cases, investigated or doubtful. (Fig. 29.)

Topaz. *Comp.*—$(F, H O)_2 Al_2 Si O_4$ (*Groth*). *Syst.*—Rhombic.

I. Rarely seen in the rock-mass, but occasionally prismatic and recognisable. The perfect basal cleavage may distinguish it from quartz. Specific gravity, 3·5.

II. *Form*—Prisms or granules. *Cleav.*—Not always seen, but good basal. *Refr. Index*—Higher than quartz (1·615) and easily distinguished thus from it with a spot-lens or oblique illumination. *Colour*—Colourless. *D. Refr.*—Colours much like those of quartz. Biaxial figure. Longer axis of prism is vibration-direction for slowest ray.

Note.—Occurs in many quartzose rocks, such as granites, greisen, &c., being probably developed from the alteration of felspars and other silicates containing alumina.

Tourmaline. *Comp.*—$H_9 Al_3 (B . O H)_2 Si_4 O_{19}$, H being replaced by Al, Na, Mg, and Fe (*Penfield and Foote*). *Syst.*—Hexagonal (Trigonal).

I. Black patches and striated prisms, sometimes in radial groups; in granites and allied rocks. Sometimes green of various shades. Occurs often on the edges of igneous veins, and is doubtless a product of the alteration of micas, felspars, and other minerals. The common black "schorl" replaces at times all the

minerals of a granite except the quartz, additional secondary quartz being at the same time developed. Not scratched by knife.

II. *Form*—Characteristic cross-sections of trigonal prisms with curved faces; or delicate needles (as in "luxulyanite"); or commonly in irregular masses spreading among the other minerals, and sometimes optically continuous around several granules of residual quartz. *Cleav.*—Irregular cracks alone visible. A fibrous structure, due to rod-like inclusions, sometimes seen. *Zon.*—Sometimes in colour. *Refr. Index*—Somewhat above that of topaz (1·636). *Colour*—Commonly a warm yellow-brown, inclining to bluish tints in places. Sometimes dull blue or green. *Pleo.*—Strong; from dark grey-brown to pale yellow-brown in common varieties. The darkest tint occurs when the shorter diagonal of the nicol is perpendicular to the longer axis of the prism. *D. Refr.*—Much like augite, but the colours are masked somewhat by the strong natural colouring of the common varieties of the mineral. Basal sections isotropic, and giving black cross with convergent light. *Opt. Sign*—Negative; the long axis of the prism is direction of vibration for fastest ray. Hence differs from prisms of hornblende.

Note.—Absence of cleavage distinguishes tourmaline from biotite and hornblende, with which tourmaline should be carefully compared. The passage into bluish tints in ordinary light is characteristic of common brown tourmaline. See note on Soda-Amphiboles.

TREMOLITE. A non-aluminous amphibole almost free from iron. Special points :—

I. Colourless, or faintly yellow or green. Occurs commonly in veins and in metamorphic rocks, often in crystalline limestones.

II. Like hornblende, but colourless.

Note.—Marked out commonly among other colourless minerals by the lozenge-shaped form of its cross-sections and by the cleavages. See Actinolite and Hornblende.

TRIDYMITE. *Comp.*—SiO_2. *Syst.*—Probably hexagonal.

I. May be seen as thin transparent hexagonal plates, several being grouped together, in the cavities of some highly siliceous lavas. Brittle and difficult to extract. Specific gravity only 2·3.

II. Seen in sections that traverse cracks and cavities in many rhyolites and trachytes. *Refr. Index*—Lower than quartz (1·48). Colourless, with anomalous double refraction in the basal plates.

URALITE (see Augite).

Zeolites.—Common as white or pale-coloured products in the joints and cavities of lavas, or among the minerals of coarser

rocks. Very often in fibrous aggregates, giving thus in sections a black cross in plane polarised light (see p. 149). For notes on some species of the group see Analcime, Natrolite, and Stilbite.

Zircon. *Comp.*—$Zr\,Si\,O_4$. *Syst.*—Tetragonal.

I. Common as a minute constituent of granites, diorites, &c., and in the sands derived from them. Ordinarily invisible to the eye; but fine brown examples occur in rocks from Renfrew, Canada, and red or yellow crystals are common in several elæolite-syenites. High lustre; hardness = 7·5. Easily separable by dense liquids, owing to its high specific gravity (4·5).

II. *Form*—When seen among the particles separated from sands, the tetragonal prism, with pyramid of another order, is commonly recognisable, the hard little crystals being only slightly abraded. In sections, small grains or squares and prisms, included in micas or other minerals. Pleochroic areas very often occur in micas round about such enclosures of minute zircons. *Refr. Index*—Extremely high (= 1·95 or more), being a little above sphene. Hence the particles in a mounted sand stand out with very black borders; while those in rock-sections have a very distinctly pitted surface. *Colour*—Colourless. *D. Refr.*—Stronger than micas; colours of high orders alone seen. *Opt. Sign*—Positive.

ZOISITE GROUP. *Comp.*—$H\,Ca_2\,Al_3\,Si_3\,O_{13}$ (compare epidote). *Syst.*—Rhombic in most cases, but the forms are closely similar to those of epidote, and a monoclinic variety, CLINOZOISITE, occurs.

I. Rarely seen in recognisable forms in rocks, though common as alteration-products. Colourless.

II. *Form*—Prisms, the longer axis corresponding to the orthodiagonal of epidote. Basal sections lozenge-shaped, with prism-angle of 116° 40′. Occur very often as decomposition-products within basic felspars. *Cleav.*—Perfect parallel to the brachypinacoid. *Refr. Index*—1·7. *Colour*—Colourless. *D. Refr.*—Much weaker than that of epidote (= about ·005); weaker even than the felspars. Hence in ordinary sections the colours between crossed nicols will appreciably aid in the discrimination of zoisite from colourless epidote. *Extinct.*—In prismatic sections not distinguishable from those of epidote. The longer axis is sometimes the vibration-direction for the ray of mean velocity, and sometimes for the fastest ray, so that the quartz-wedge gives different results for different species.

Note.—Compare epidote (pistacite), and tremolite. See also saussurite, and especially Weinschenk, *Gesteinsbildende Mineralien* (1901), pp. 81-88.

CHAPTER XVIII.

SEDIMENTARY ROCKS.

To proceed to the application of the methods of observation that have been now described, we may begin with fragmental or clastic rocks, as being on the whole the most frequently met with and being in many cases capable of simple examination in the form of powder under the microscope. As in the case of rock-forming minerals, under the heading I., in dealing with each type of rock, we shall describe the characters that ordinarily serve for its determination in the field or in a hand-specimen, while under the heading II. we shall point out its most striking microscopic characters.

I. Sands and Sandstones.

Sand.—Composed of loosely aggregated grains of quartz, various silicates, or other minerals; in the vast majority of cases, rocks described as sands possess a large percentage of silica.

I. Sands should be collected in as dry a condition as possible, and from positions where they have not been sifted by local air-currents. Specimens can be easily carried in strong pill-boxes in a dry state, or, very conveniently in stout glass specimen-tubes, corked, the tubes themselves being protected in a little flat box carried in the field-bag. Shell-fragments, spines, spicules, and so forth, can generally be separated by sieves, and the character of the inorganic mineral granules can then be studied separately. The mud or other obscuring particles on the surface of the grains should be rubbed off as far as possible with the fingers, and, when thus loosened, can be blown off or washed away in water. Where the first signs of cementation and of the conversion of the sand into a sandstone have made their appearance, the chemical or other characters of the cementing material must be carefully examined.

For many observations it is necessary to clean the grains with acid; limonite, calcite, &c., are thus removed, and the residue commonly emerges from the test-tube in an almost colourless condition.

Where it is desirable to divide a sand into constituents of various degrees of fineness, as during the examination of a soil, zinc sieves with circular holes are in every way superior to the ordinary tin ones with wire meshes. Commercial perforated zinc can be used for the bottoms, the holes being commonly graded in millimetres. For quantitative work, the residue in the sieve must in all cases be washed with water, and the fine material thus carried through must be passed through the next sieve lower in the series, and so on. For the separation of grades below 1 mm. in diameter, processes involving successive sedimentation in water or elutriation should be employed (see p. 115, and T. Crook on a method of soil-analysis, *Economic Proc. R. Dublin Soc.*, vol. i., p. 267). It may be remarked here that many plastic "clays" are found to consist in part of very fine quartz sand (see p. 198).

The use of heavy liquids (p. 116) will be invaluable in all cases of research. The extraction of heavy minerals, such as zircon, rutile, &c., from common sands may also be effected very fairly by the following method described by Mr. Carus-Wilson.* A piece of cardboard about 2 feet long is bent in the form of a trough and held in this curved form by elastic bands at either end; this is held at an angle sufficiently steep to allow the sand to travel slowly down when the cardboard is tapped with the finger. The heavy minerals, commonly appearing as very small dark grains, lag behind, forming a continually increasing crescent-shaped group at the upper end of the descending material. When the last common sand-grains have fallen off, this heavier portion may be collected in another vessel. There will be a number of minute quartz grains, &c., still associated with the rutile or zircon; but these can be largely removed by blowing lightly; even if a separation in dense liquids becomes finally necessary, the work will have been very greatly facilitated by this simple and effective preliminary method.

Sands derived from volcanic rocks and from other igneous masses frequently contain magnetite, which can be easily picked out by the magnet. Even olivine has been recorded as forming whole beds of sand, which in the future may produce an anomalous and stratified deposit of serpentine. It must be remembered, however, that even in common sands the particles are not necessarily homogeneous, many of them being the relics of rock-fragments rather than simple minerals. Tiny pebbles of iron-bound sandstone, of quartzite, of chert, or of the matrix of old

* *Nature*, vol. xxxix. (1889), p. 591.

highly silicated lavas, are common among the constituents of sands.

In the field, the stratification of fine sands is often worthy of study, and current-bedding is a very common feature. Owing to the yielding nature of the deposit, local contortions sometimes occur through the pressure or slip of beds above. The bleaching of ferruginous sands by vegetation can be characteristically observed upon any sandy heath.

II. The outlines of sand-grains can be well studied microscopically in water, a cover-glass being pressed down upon the preparation. But the grains should always be examined as a preliminary by reflected light, being simply scattered on an opaque card and brought under the microscope. If much surface-coating is present, it may be necessary to treat the particles with dilute warm acid in order to render them clean and transparent for subsequent observations.

The forms of the grains, quite apart from the question of rounding, resolve themselves into some three groups:—(*a*) ordinary granules, irregular or spheroidal; (*b*) rod-like bodies, sometimes seen to be well preserved and well terminated crystalline prisms; and (*c*) platy forms, commonly with very irregular boundaries.

Every worker should be acquainted with the already classic address by Mr. Sorby,* delivered to the Geological Society in 1880, which abounds in practical suggestions, as well as in results of the widest interest. The present remarks relating to fragmental rocks are naturally based largely on the observations then put forward.

Thus Mr. Sorby notes that the difference between granules and platy forms, not always to be determined by focussing the instrument on various parts of the surface, may be seen by pressing the cover-glass above the particles mounted in water. The granules roll over and thus show changes of form; while the little plates glide along, rotating only parallel to the plane of the glass slip.

Polarised light aids greatly in such observations; for a series of coloured rings or zones, which are fairly parallel to the outline, appears if a grain is present, since it becomes thicker from the margin inwards. Platy forms commonly show similar rings at their frayed edges; but the central area gives a uniform colour, being bounded above and below by parallel surfaces.

The degree of rounding of the grains must be studied by

* *Quart. Journ. Geol. Soc.*, vol. xxxvi. (1880), Proc., p. 46. See also *Monthly Microscop. Journ.*, 1877; Anniv. Address.

transmitted and reflected light. Mr. Sorby, in comparing one sand with another, uses sieves that separate grains for examination having a diameter of about $\frac{1}{100}$th of an inch. The finer the grains, the less the degree of rounding; and it is obvious that very cleavable or friable materials will be incapable of comparison with such substances as quartz. Thus some constituents become quickly reduced to minute particles, and thereafter suffer little physical change; others exist as minute crystals in the rock from which the sand is derived, and these may retain their forms through a very long series of natural triturations.

Mr. Sorby and Mr. J. A. Phillips* have pointed out that the most rounded and polished grains are found in sand accumulated on land-surfaces, as in deserts. Thus some of the Bunter sands of Lancashire and Cheshire "flow between the fingers as readily as shot," and were very probably blown against one another in some Triassic desert. The process even here must continue for a considerable time, since the ordinary drifted sands of sea-side dunes show little rounding; while it would be difficult to find a parallel among the polished sands of modern deserts for the remarkably smooth and globular constituents of the Triassic "millet-seed sands." Where, then, the majority of medium-sized grains in a sand are strikingly rounded, the deposit has been formed by æolian agency, or by rivers bringing down such materials from the land.

It must be borne in mind that the more heterogeneous the constituents of a sand, the nearer it is likely to be to the place of origin of the materials. But any sand may have been cemented into a sandstone, and again broken down into a sand, in several geological periods, and denudation combined with earth-movements may have long since removed the rocks of which its grains were original constituents. On our own southern shores it is most interesting to reflect on the mingling together of granitic quartz, and of Triassic, Portlandian, Cretaceous, and Oligocene sands, to form later sandstones which will be assigned to the opening of the human period.

The grains of *quartz* that compose so large a part of ordinary sands, when cleaned from their superficial coatings, show an absence of prismatic forms and cleavage-surfaces, and are generally pitted and covered with small grooves, when seen by reflected light. By transmitted light the strings of liquid-enclosures, characteristic of rocks that have at one time been deep-seated, frequently become visible. At other times, relics of glass that

* "On the constitution and history of grits and sandstones." *Quart. Journ. Geol. Soc.*, vol. xxxvii. (1881), p. 12.

has intruded into the grain point to its having existed in a volcanic magma. The deposition of crystals upon the grains will be treated of under the head of sandstone (p. 192).

The bright colours of the quartz in polarised light, running in zones that rise towards fourth order colours at the centre, serve to pick out the granules among duller and heterogeneous material.

Particles of *flint* are comparatively rare, even in the finer materials of flint gravels; though in some sands they contribute by their abundance to the dark colour of the mass.* The chips are typically angular and small, and show with crossed nicols a minutely granular structure, the grey speckled effect being constant during rotation, and the whole never becoming extinguished at the same time. Particles of white flint may be seen in some gravels by reflected light, and may be picked out and tested with acids. Some of these show traces of the structure of siliceous sponges (sand of Chipstead, &c.) Others result merely from the alteration of fragments of originally black flint.

Felspars give generally rounded grains, which are almost opaque in water, and are, if large, not very translucent in balsam. By reflected light they appear milk-white, or brownish or pinkish-red. These effects of earthy decomposition are very characteristic, although clearer examples, even showing repeated twinning, occur near the place of origin of many sands. It must be remembered that a prismatic doubly-refracting plate thinner towards one edge than the other will give with crossed nicols a series of coloured bands, which may simulate twin-lamellæ; but the colours will not be alternately complementary, but will rise in the order of Newton's scale as they recede from the thin edge.

The *Micas* show flat irregular plates, the edges descending in minute steps, owing to the cleavage. But for this indication, the cleavage is not noticeable, since the plates will not stand up edgewise in the preparation. This fact is important also in observing pleochroism, since the almost uniaxial character of common dark mica prevents the change of tint from appearing in basal flakes. The lustrous surfaces of the micas enable them to be detected in the dry sand by reflected light.

Amphiboles and Pyroxenes give more or less prismatic fragments, with signs of cleavage and a fairly robust appearance. The pleochroism of the former group aids in its recognition.

Tourmaline occurs often in sands derived from granites, yielding conchoidally fractured grains or prisms, of dark brown green or other colours. Strong pleochroism, the darkest tint

* Miss M. I. Gardiner, "On the Greensand Bed at the base of the Thanet Sand." *Quart. Journ. Geol. Soc.*, vol. xliv. (1888), p. 756.

occurring in the reverse position to that of hornblende—*i.e.*, perpendicular to the longer axis of prismatic forms.

Magnetite is opaque black, verging into the brown of the "ironstone" grains that are also frequent in sands. These opaque brown grains often consist of the material, such as *limonite*, by which the sand may ultimately be cemented.

Kaolin gives in water, on pressure of the cover-glass, tiny platy particles and much excessively fine dust. In water or balsam the doubly-refracting character enables the crystals to be picked out from the mere amorphous or minutely divided mud. Opaque white by reflected light.

Glauconite, a general name for the green silicates that form in hollows of foraminifera, &c., is granular, the grains being commonly composed of smaller ones, and retaining in many cases some trace of the form of the foraminiferal chambers in which they first consolidated. Colour dark green to green-black by reflected light; by transmitted light earthy to clear green, yellow-green or brown-green. A very common soft constituent of the greener beds of sand in all formations.

The heavy minerals that appear on separation from the bulk of the constituents of a sand are mostly iron ores, tourmaline, zircon, and rutile. Mr. Allan Dick found in a bed of the Lower Bagshots at Hampstead about 3 per cent. by weight of these constituents. *Zircon* exhibits colourless strongly refracting ovoid or prismatic rods, the prisms being frequently terminated by only slightly abraded planes of the pyramid. Enclosures of rod-like crystals may be seen within the zircons. *Rutile* appears as orange-brown granules or prisms, the characteristic heart-shaped or geniculated twins being occasionally present. The outlines of the forms are very black, owing to the exceptionally high refractive index.*

Finally, the rock-fragments that may occur in sand, even on a very minute scale, must be considered apart from the pure minerals; but their study is beset with difficulties, and specimens from the coarsest varieties of the sand-beds can alone give satisfactory indications.

Grits and Sandstones.—I. These may be studied by rubbing up with the fingers or a stiff brush (not by crushing) until the individual constituents are released. The cementing matter must be examined chemically; in many cases the cleavage-surfaces of calcite can be seen gleaming between the grains, which have become, indeed, set in ophitic crystals of the cement.

* See Teall, *Microscopic Petrography*, plate 44.

Barytes occurs in some cases, and silica is common. Dark iron oxides cement sandstones at times in bands and patches, and casts of fossils, though lost in the rock, will be found occasionally preserved in these consolidated parts of it.

In the so-called "crystalline sandstones," known in Britain through their occurrence in the Permian, the grains show crystal-facets of quartz, easily seen in coarser cases with the lens. Mr. Sorby showed how these crystals resulted from the deposition of silica upon original rounded grains, the interstices between them becoming finally filled with this clear secondary quartz.

II. This question receives even greater interest from the application of the microscope. If the grains thus coated with faceted quartz are treated with acid to remove limonite, &c., the original internal grain becomes visible by transmitted light, and the secondary deposit is found to be in optical continuity with the original quartz, being in fact a restoration or perfecting of the abraded granule. At times only the first signs of such crystals appear on the surfaces of ordinary grains, showing as bright little pyramids when reflected light is used. It has been suggested, on the other hand, that some grains become corroded by solution of the surface after the consolidation of the sandstone.

Should the original grains be completely enveloped in new quartz and their independent outlines lost, it is evident that the union of the coats belonging to adjacent grains will take place along irregular surfaces, and a number of interlocking granules will appear in section, each giving a uniform tint between crossed nicols. Such a structure is characteristic of the quartzites about to be discussed.

Sections of consolidated grits and sandstones are particularly valuable for the study of cementing materials. Calcite, or aragonite, is sometimes deposited in fibres between the grains; in other cases a chalcedonic cement has resulted from the solution of spicules of sponges scattered through the sand-bed, the casts of which, or of their tubules, still remain. This matter will be again referred to under chert.

Prof. Bonney* has remarked on the rarity of chalcedony as a cementing material among the older rocks. It is quite possible that a slow passage into the condition of quartz takes place, and the continuously crystalline appearance of the granules of ordinary quartzite becomes thus finally set up.

The ferruginous cement of many dark red sandstones and

* "On the Ightham Stone," *Geol. Mag.*, 1888, p. 299.

"carstones," like certain layers in the Folkestone Sands, is almost opaque in sections.

In grits the constituents can be easily studied in section; the felspars often appear prominently, as in rocks formed close against a granitoid or gneissic area. The Torridon Sandstone of N.W. Scotland is a fine example. (Frontispiece, fig. 2, and p. xiii.) The larger quartz fragments are frequently seen between crossed nicols to be compound, being in fact quartzites and derived from pre-existing consolidated sandstones. The close examination of the rock-fragments in coarse grits gives one a very fair idea of the nature of the land-surface over which the denuding and transporting agents worked. We must remember, however, that limestones and clays go to powder readily, and are only feebly represented in these final accumulations.

In an old volcanic district, the consolidated grits and gravels, seen in section, give one very valuable information as to the rocks that were first attacked by denudation. Thus the glassy scoriaceous surfaces of lava-streams become early broken up and reduced to fertile soils and red bands of "laterite;" but in the gritty accumulations of the rivers that flowed through the volcanic area we find rolled fragments of these surfaces preserved in considerable abundance.

There is often considerable difficulty in deciding as to whether fragments of lava, occurring in a sandstone, point to contemporaneous volcanic action. A rock may not be an actual tuff, and yet may derive much of its materials from adjacent tuffs, which were formed, perhaps, only a few days before its own period of accumulation. Here the microscope aids us in estimating the relative antiquity of the igneous fragments. Their degree of freshness, particularly when they consist of pumiceous glass, becomes a useful guide. Where, however, they are minute and shred-like, we must remember that the explosive action which produced them, although truly contemporaneous, may have occurred a hundred miles or so from the site of the sandstone in which they are embedded.

Sandstones formed close against a mass of granite, or similar plutonic rock, may sometimes closely imitate the igneous mass, especially when seen in section. The fine-grained "arkose" produced under such conditions contains all the minerals of the igneous rock, closely set, and fitted into one another by the pressure of overlying strata. But it must be remembered that the ferro-magnesian minerals, the micas and so forth, of the original igneous rocks are those that develope first, and secure their characteristic outlines. Here, however, in the reconstructed rock or arkose, they will have no superiority of form, and will

often be crushed against and folded round the more resisting grains of quartz and felspar.

Quartzites.—I. A certain amount of difficulty has been made as to the distinction of "quartz-rock" (massive quartz) and quartzite; but the former rock typically occurs in veins, as a product of hydrothermal action, and is formed of coarse interlocking and irregular quartz crystals. The quartzites, on the other hand, are divided by a number of small joint-planes, often show traces of bedding, and almost invariably reveal their granular structure on close examination with the lens. Any grit or sandstone with a siliceous cement may be regarded as a quartzite, and the pocket-knife readily detects this essential character. The best types, however, are those in which the individual granules have become merged, as it were, in the cement, which has settled down in crystalline continuity with the several grains. The surface of such rocks, and of the cement in other types, presents a characteristic almost vitreous lustre, and is broken up into a number of minute glancing points. The colour of the rock is commonly pale grey with yellower or browner joint-surfaces, the iron having passed away along these during the slow alteration of the mass. Many quartzites, like those of the Wicklow Sugarloaf and the cappings of the Torridon hills, are almost pure white, and can be seen as gleaming crags at a considerable distance.

The specific gravity is practically that of quartz or a little higher (about 2·67). Acids merely spread over the surface without effect, and the hardness at once forbids any confusion with grey dolomite. Even the compact eurites, of igneous origin, are almost invariably softer than typical quartzites.

The bedding-planes of the original sandstone are very often obscured, and the fracture of the rock is irregular to conchoidal. The foliated metamorphic quartzites will be discussed under quartz-schist.

II. In section the quartzites are clear and colourless, with occasional signs of the original granules. With crossed nicols a brilliant interlocking mosaic of quartz areas appears, the effect of which may be intensified in the metamorphic types by crushing (see fig. 44).

II. Fragmental Volcanic Deposits.

While volcanic sands are mere waterworn deposits that have derived their materials from some neighbouring volcanic area, there is a great group of rocks, often well stratified, that is formed directly by volcanic accumulation.

Volcanic Agglomerates or Coarse Tuffs.—The constituents are blocks of volcanic or more deeply seated rocks, angular and often of considerable size. These are frequently scoriaceous and amygdaloidal, and represent the more vitreous parts of lavas. Spheroidal bomb-like forms may be looked for, as well as twisted ropy types, coloured externally a rusty brown. The groundmass is formed of similar smaller fragments and fine dust, and the whole becomes in older examples as firmly cemented together as a conglomerate, the joint-planes traversing the included blocks and the binding material alike. The great weathered joint-surfaces of such rocks are valuable for study in the field, as the materials of different composition and hardness stand out on them distinctly from one another, and sections are in addition provided of the bombs and other ejected blocks. Sketches must be made on the spot, as it is impossible to adequately represent such masses in hand-specimens.

The fragments torn from stratified deposits and thrown out into the agglomerates, particularly when the eruption was submarine, are well contrasted with the igneous matter. We may note as examples the great flakes of shale to be seen in the blocks under Tyrau-mawr on Cader Idris.

Tuffs and Ashes.—I. The tuffs are so often altered soon after deposition, owing to the attacks of volcanic vapours, that their former loose character is lost, and they appear compact and even uniform on newly fractured surfaces. Weathering, however, reveals the coarsely fragmental structure, and developes again the scoriaceous character of many of the included blocks. Examples of the weathered surface should always be collected. The beds will be found, on tracing out, to vary considerably and rather rapidly, and to present, if deposited on land, marked variations in thickness.

The loose tuffs of late Tertiary volcanoes are readily recognised. The embedded crystals, such as augite or felspar, and the blocks of lava, will enable one to ascertain the character of the materials that rose in the volcanic vent. Earlier and consolidated beds will, however, be sometimes blown to pieces and mingled with these fresher layers.

The finer ashes form very compact beds that require the microscope for their determination. In many, particularly when spread out by water, there is the most delicate stratification, and the older varieties resemble grey or greenish slates. Concretionary lumps may be formed in them, simulating at first sight the fragments in a tuff.

II. The study of tuffs and ashes under the microscope is of immense interest, owing to the various types of volcanic rock that are found thus thrown together. An abundance of glassy particles, often in mere shreds or conchoidal wisps, characterises the groundmass in most cases. Even in ancient examples, the forms of these remain strikingly apparent (fig. 22). The larger lumps must be compared with their representatives among the lavas, but a preponderance of glassy types may be expected.

Fig. 22.—Altered Andesite-tuff—Snead, near Bishop's Castle, Shropshire. × 14. Fragments of various lavas, more or less devitrified, with crystals and fine compacted interstitial ash. *a*, Compact andesite or aphanite. *f*, Ejected crystals of felspar, probably derived from the breaking up of pumice. *p*, Perlitic and formerly glassy andesite. *pu*, Pumiceous and vesicular fragments of altered andesite-glass.

In fine compacted ashes it may be impossible to determine in section the volcanic origin of the material; but modern examples can be mounted in balsam like sands, when a mixture of pumiceous glassy fragments and crystals of various constituents becomes easily visible under a $\frac{1}{4}$-inch objective. The crossed nicols serve to pick out the crystals from the glass, the felspars appearing as brightly coloured cleavage-flakes. The careful microscopic study

of such recent materials encourages one to cope with very dubious "slates" and indurated beds which may prove to be of volcanic origin.

The minerals developed by secondary action in tuffs and ash-beds seldom obscure the structure when the microscope is used. Even fluor-spar arises at times; and the vitreous matter becomes commonly altered to greenish softer products, when basic in character, or to anisotropic granular areas when more highly silicated. The form of the wisps and shreds of glass is, however, well preserved, even in some ashes of very ancient date.

A brecciated lava may often be distinguished from a tuff by the adjacent fragments being clearly broken apart from one another, veins of new minerals or crushed materials filling the gap. Lavas may often pick up fragments of their own cooled surfaces or of beds over which they pass, and the microscope must prove the continuity and formerly fused character of their matrix before they can be well distinguished from tuffs. Products of crystallisation from the fused mass, such as spherulites, &c., will in such cases often be seen round the included fragments, and the edges of the fragments may show signs of remelting, or of secondary crystallisation. (See p. 99.)

Fine-grained ashes, again, may pass into true sedimentary deposits through being accumulated under water or by the flow of rain-floods down the sides of the volcano. Microscopic evidence will hint at this mingling of material, but such suggestions must be worked out fully in the field.

Finally, the materials of any one deposit are likely to give only a limited notion of the nature of a particular eruption, or of the rocks extruded, since a sifting of a very complete character may go on in the air, the compacter lava-framents falling nearer the volcanic centre, the crystals embedded in vesicular glass being carried farther, and the fine pumice being deposited to form considerable dust-beds at a distance of even several miles.

III. Clays and Shales.

I. The plastic nature of clays when freshly collected, and their easy sectility when dry, the cut surface appearing polished, are characters known to every one. Any change of colour should be noted in a clay-pit as deeper beds are approached, for the suspicion of alteration hangs over most brown clays. The red streaks of the "mottled clays" seem due to the introduction of iron-salts by permeating waters, calcareous matter going into

solution from the clay (Moody, *Quart. Journ. Geol. Soc.*, 1905, p. 431).

The analysis of soils has shown that some of the materials known as clays consist essentially of finely comminuted quartz grains. The qualities of plasticity and practical impermeability do not depend always on mineral constitution; on the other hand, ordinary clays contain some 20 per cent. of alumina, while some yield 38 per cent. of alumina and 46 per cent. of silica, showing that they consist almost entirely of kaolin. To detect admixtures of coarser matter, which may give some hint of the source of the clay, the material is broken up, without violence, and *thoroughly dried.* The pieces are now immersed for twenty-four hours in water, when they break down easily to a very fine mud, which can be washed gradually away (see p. 114). Repeated washing in a broad dish will serve all ordinary purposes, the fine muddy material being poured off at intervals. The residue will consist of the coarser sand, selenite, iron pyrites, &c.

Small fossils, such as entomostraca and foraminifera, may be similarly extracted. Their very smallness allows them to retain delicate spines and structures upon their surface when larger shells have been entirely broken up by natural or artificial pressure.* A quite moderate amount of water, so as to allow of slight friction of the mud-coated organisms against one another, assists their cleansing; the fine mud, as a safeguard, may be decanted off through muslin; in some cases fine silk is necessary.

Marls, truly so-called, may be detected by their partial effervescence with hydrochloric acid, the shelly or inorganic admixture of carbonate of lime readily betraying itself.

Loams, on the other hand, are recognisable by the large proportion of gritty matter, insoluble in acid, that remains behind after washing.

The beautiful laminated structure of some clays become more apparent where the materials are more consolidated and the rock passes into shale. On the surfaces of such beds delicate fossils must be looked for, the leaves of Tertiary deposits, the Wealden entomostraca, the plant remains of the Coal-measures, and the impressions of the graptolites, being familiar examples. Very fine calcareous beds, like parts of the Solenhofen "slate," resemble some pale shales, but can at once be distinguished chemically with acid. Among the older rocks there is a tendency for shales to become darker than the corresponding modern stratified

* *Scientific News*, vol. i. (1888), p. 141; also Praeger, "Estuarine Clays," *Proc. R. Irish Acad.*, 3rd ser., vol. ii. (1892), p. 218.

clays, and graphitic matter becomes finely disseminated by organic decay. The fissility of the layers, due to shrinkage and pressure of upper deposits, is the essential character of these shaly forms. See also Concretions later.

Bauxite is not a true clay, but is commonly mixed with clay, and is found in association with ordinary sediments. In some cases, as in the laterites studied by Dr. T. H. Holland (*Records Geol. Survey, India*, vol. xxxii., 1905, p. 175), it has clearly arisen from the decay of igneous rocks rich in alumina. It is a compact or pisolitic mass, cutting like clay, adhering to the tongue, and grey or cream-coloured. Some varieties are strongly red, through abundance of iron. Except for impurities, bauxite is soluble in sulphuric acid, and forms the one source of commercial aluminium.

II. Under the microscope the minute particles of kaolin are platy or merely dust-like, but distinctly affect polarised light. Quartz grains stand out, with vivid interference-colours, and fragments of shells show the strong double refraction of calcite or aragonite, often with black crosses due to minute radial aggregates. The residues after washing resemble sands; care must be taken that mica flakes, which may be numerous, are not washed away completely with the light material, on account of their easy flotation. The rutile is extremely minute; but in many clays the titanium dioxide, as shown by analyses, amounts to over ·30 per cent.

Crystals or cleavage-flakes of gypsum (selenite) are not uncommon, recognisable by their angles and low polarisation-colours. Glauconitic grains may also be expected.

Some clays and shales contain pumiceous and other volcanic particles, and graduate into the subaqueous ash-accumulations already described.*

IV. Limestones.

General Characters.—The colours of limestones are very various; but the hardness, about 3, helps greatly in the detection of these rocks. While at times finely granular limestones resemble quartzites, and dark varieties even imitate compact basaltic lavas, the knife readily settles the question, and leaves a well marked scratch, filled with white powder, across the limestone.

* For microscopic details of clays and slates, see W. M. Hutchings (*Geol. Mag.* 1890, 1891, 1892, 1894, and 1896) and B. Zschokke (*Bull. Soc. d'encouragement pour l'industrie nat.*, vol. ciii., 1902, p. 654).

The specific gravity is generally rather under that of calcite, probably owing to porosity and impurities. Some compact varieties give only 2·6, while the dolomites run up to about 2·85. Varieties with much aragonite will give 2·8. With hot acid all varieties effervesce freely. The ordinary limestones do so when a drop of cold acid is laid upon them.

Meigen's test will distinguish aragonite in these rocks from calcite, while Lemberg's test will mark out calcite from any dolomite that may be present (see p. 36).

The residues after solution (see p. 120) are often of extreme interest. Sand-grains are of course common, with glauconite, tremolite, flakes of mica, &c. But in many cases silicified organic structures may appear; and in the Carboniferous limestones doubly terminated quartz crystals have been frequently noted, containing impurities from the limestone, in which they have been developed after its consolidation. Mr. E. Wethered has found these, in the Clifton limestones, formed round detrital sand-grains, just as the secondary quartz is deposited in the sandstones already described.* Planes of lamination, though they may be quite apparent, as in some Tyrol dolomites, do not necessarily form easy planes of separation. The distinct vertical joints, passing down through many feet of strata, give, with the bedding-planes, the well known block-like character to exposed limestone surfaces, and tend to perpetuate the terraced cliffs so familiar in the field. In the hand, compact limestones break through with a clean fracture in almost any direction, the surfaces produced by trimming being conchoidal in those of the finest grain.

Mr. Sorby observes that the fissile character of the Stonesfield "slate" is due to laminæ from the shells of *Ostrea* and brachiopoda. Another point brought out by his extended series of studies and comparisons† is the frequent occurrence of small rolled fragments of earlier beds of limestone in those of later consolidation.

Concretions of silica (flint and chert), and the replacement of whole beds by pseudomorphic action, are common features of limestones of every age. The character of the products of such action will be discussed in the seventh division of this chapter.

The faces of cracks in limestones, and the surfaces of hollows and caves, will be commonly found coated with stalactitic crusts, often of great delicacy. Similar deposition upon leaves, twigs, &c., from springs containing carbonate of lime, gives rise to travertine or "calcareous tufa," the interspaces becoming finally filled up

* *Quart. Journ. Geol. Soc.*, vol. xliv. (1888), p. 186, with figs. of residues.
† Presidential Address, 1879. *Quart. Journ. Geol. Soc.*, vol. xxxv., p. 56.

with calcite and the whole mass consolidated into a limestone showing vegetable impressions.

Shelly Limestones and Chalk.—The modern representatives of these rocks are found in our shell-banks, in the white accumulations of fresh-water shells in lake-floors (commonly styled "shell-marl"), and in the calcareous oozes of deep seas. Seeing that, as Mr. Sorby has shown, followed by Messrs. Cornish and Kendall,* there are numerous organisms that construct shells of aragonite, while other shells consist of calcite, and yet others of layers of both these minerals, we must expect to find both forms of carbonate of lime in association. The instability of aragonite, however, gives rise to pseudomorphs in granular calcite, or to the total removal of the shells originally built up by it. Hence calcite becomes the prevalent constituent of consolidated limestones. In judging of the fauna to be found in these rocks, allowance must be made for the solubility of the aragonite shells, and search must be made for impressions and casts. Thus porcellanous foraminifera,† the skeletons of corals, many lamellibranchs, and most gastropods, may be absent from permeable rocks in which they once existed in abundance. Messrs. Cornish and Kendall show how below the saturation-level such shells may be preserved, though in a crumbling condition, while in the beds through which the water actually flows they become entirely removed, the calcite shells being also affected along well-marked lines of flow.

I. In the field the shells should be looked for upon weathered surfaces, or upon the marked bedding-planes of the rock. Many slab-like masses seem unproductive until split open parallel to the stratification. Careful chiselling away, after collection, with a small chisel or a blunt knife-end, and steady cautious friction with a tooth-brush, dry or under water, will reward the worker who has time for the development of choice specimens. Calcite shells have a somewhat transparent appearance in small fragments; aragonite shells are more porcellanous and dull, and *will scratch the surface of a calcite crystal.* The remarkably uniform crystallisation of the calcite in echinodermal remains, whether tests, spines, calyxes, arms, or stems, enables one to pick out these bodies upon fractured surfaces of limestone. The calcite cleavages are continuous throughout each "ossicle," as may readily be seen in the tests of the numerous echinoidea of

* "On the Mineralogical Constitution of Calcareous Organisms." *Geol. Mag.*, 1888, p. 66.

† Sollas, "On Sponge Spicules, &c.," *Journ. R. Geol. Soc. Ireland*, vol. vii., p. 46.

the Chalk or in the stems of Carboniferous crinoids. Other shell structures, like the pearly folia of the oysters or the fibrous fractured surfaces of *Inoceramus*, can be characteristically recognised on rough surfaces of limestone. Pseudomorphs of the fossils in carbonate of iron, silica, hæmatite, &c., are by no means uncommon.

II. While shell-sections can be well studied with a lens in quarries of fossiliferous limestone, the microscope affords much material for careful observation. The recognition of the various organisms is naturally difficult in sections, and recourse must be had to the solid types in the rock-specimen itself. Foraminifera, as in chalk, suggest their presence by the multiplicity of their chambers and by a number of detached thin-walled circular sections. The slides should be of large size, and sections are then sure to occur which pass conveniently through certain forms and reveal the true relations of the chambers. In Cretaceous chalk there are the curved forms, like scimitars, of larger shells, more transparent than the calcareous mud that forms the groundmass; and occasionally the rectangular fibrous sections of fragments of *Inoceramus* lie scattered through the slide.

When chalk is carefully broken up and washed, as in a muslin bag under a flowing tap, the foraminifera may sometimes be extracted solid, and can be mounted as if they were part of a modern ooze. By rubbing up with a tooth-brush, a fine white mud is produced, which shows abundant coccoliths, like those of existing seas, when examined with a ¼-inch or ⅛-inch power. This process of separation is sometimes naturally performed in the fine detrital mud to be collected at the base of chalk escarpments. (*Cf.* Chapman, *Proc. Geol. Assoc.*, vol. xvi., 1900, p. 268.)

Sections of chalk are by no means difficult to prepare, but must be finished without emery and with a delicate hand. The harder beds that occur at certain levels may conveniently be chosen for this purpose.

In some sections of chalk, as in specimens from the Chalk-Rock and Melbourn-Rock (the upper and lower limits of the British Turonian), the fact that the bed is partially constructed of fragments derived from earlier layers is well displayed and has an important stratigraphical bearing.*

Sections or polished surfaces of shelly limestones parallel to the stratification and perpendicular to it will naturally present very different characters, and will, in cases where weathered

* See Prof. Judd, "Jurassic Deposits under London," *Quart. Journ. Geol. Soc.*, vol. xl. (1884), p. 733 and plate xxxiii. Also Hill and Jukes-Browne, *ibid.*, vol. xlii. (1886), p. 229.

surfaces are not available, be of service in determining the true forms of the embedded fossils.

The material between the fossils and filling their cavities is found to be a detrital mud ground from shell-fragments, or distinctly crystalline calcite which has gradually developed. Since carbonate of lime forms minute crystals even in ordinary chemical precipitation, the occurrence of well-developed granules in sections, with characteristic signs of cleavage and twinning, must not be taken as evidence of extreme metamorphism, but rather as the natural accompaniment of the consolidation of the mass. (Pl. I., figs. 1 and 2.)

Coral-Limestones.—Scattered corals occur in many shelly limestones; but occasionally the branching or astræan types build up reef-like masses among ordinary sediments, enclosing the coral-detritus accumulated on their flanks, together with many remains of the organisms of the external sea. These coral limestones can be well studied in polished surfaces, which often, by contrasts of colour, show more than thin sections, in which the crystals of calcite, in the walls as well as in the interstices, obscure the definiteness of the outlines. (Pl. I., fig. 3.)

In coral-limestone, the aragonite of the skeletons or of the cementing material passes readily into calcite, while dolomitisation may further obscure the original structures. (Compare Skeats, "Dolomites of Tyrol," *Quart. Journ. Geol. Soc.*, vol. lxi., 1905, p. 126, &c.)

Limestones formed by Calcareous Algæ.—The calcareous algæ, such as *Halimeda* (aragonite) and *Lithothamnium* (calcite), contribute very largely to the massive rock known as coral-limestone, and sometimes form independent reefs. In hap-hazard sections their elongated cells, in rows one above the other, may be taken for polyzoan or corallian structures. The Lithothamnium-beds of the Vienna basin are an example.

Pisolitic and Oolitic Limestones.—I. Treating the first-named of these as merely a coarse variety of the second, these rocks have the following common characters. On weathered surfaces, and on fractured surfaces of most Mesozoic and later types, distinct ellipsoidal and spherical bodies are visible, usually forming the bulk of the rock and of the same pale colour as the groundmass. In chemically altered types they become darker than the interstitial matter, appearing brown, red (Clifton), or black (Hirnant limestone). With the lens, concentric structure about a compacter nucleus is frequently clearly seen; the nucleus is often a fragment of some fossil.

In pisolitic limestones these bodies are irregularly ellipsoidal and often flattened, and even resemble thick nummulites in some examples.

The oolitic grains formed among the modern coral-reefs of the West Indies, or in the great Salt Lake of Utah, and studied by De la Beche,* Sorby, and others, are doubtless comparable to the components of the oolitic rocks that occur among the formations of all ages.

In the majority of cases, the material deposited is aragonite, which has altered to calcite in the "fossil" examples. Herr G. Linck's observations on this point are of special interest, and strongly support the view that oolitic structure has a simple inorganic origin (*N. Jahrb. für Min.*, *&c.*, Beilage Band xvi., 1903, p. 509).

It may happen that the original structure of a limestone is entirely destroyed by crystallisation. Even then its former character may be detected in the chert-bands that developed at an early period in the mass. Thus the chert of the Assynt limestone at Stronechrubie, Sutherland, preserves in the most exquisite manner the oolitic structure that doubtless once prevailed throughout considerable masses.

II. In section the oolitic grains show a delicate concentric structure, with occasionally, in addition, a radial grouping of the components. The central ovoid nucleus is often large in proportion to the grain, and is a fragment of some fossil, a foraminifer, a sand-grain, or, very commonly, a rounded detrital lump of limestone-mud on which the concentric layers have accumulated. Many sections of the grains show no nucleus, the central portion not being included in the thickness of the slide.

Mr. E. Wethered† has noticed that the grains of certain pea-grits and oolites abound towards the exterior in convoluted tubular markings. Such delicate tubes are also clearly seen in sections of the West Indian grains. They have since been shown to be, in some cases, due to the borings of algæ, such as penetrate many shells. (See *Quart. Journ. Geol. Soc.*, vol. xlvii., p. 367, and Bornet and Flahault, *Bull. Soc. Botanique de France*, t. xxxvi., p. 147; also *Nature*, vol. xliii. p. 185.) It

* *Geological Observer*, 2nd edition, p. 106; G. K. Gilbert, "Lake Bonneville," *Monograph* i., *U.S. Geol. Surv.*, p. 169; Rothpletz, abstract in *Neues Jahrb. für Min.*, 1895, Bd. i., p. 307; &c.

† *Geol. Mag.*, 1889, p. 196; also *Quart. Journ. Geol. Soc.*, vol. xlvi., and vol. li., p. 196; Harris, *Proc. Geol. Assoc.*, vol. xiv., p. 59; and Teall, "Jurassic Rocks," vol. iv., *Geol. Surv. United Kingdom*, p. 8.

Plate I.

LIMESTONES.

Fig. 1.

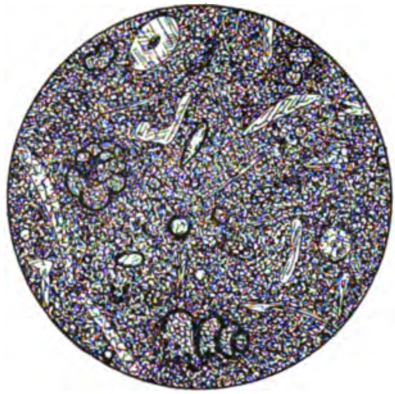

Fig. 2.

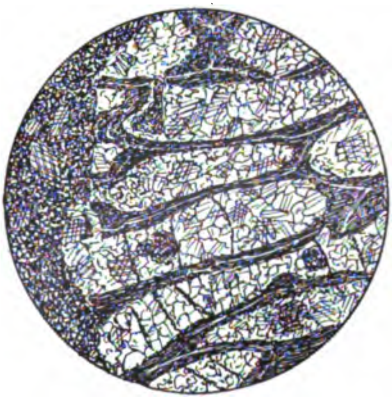

Fig. 3.

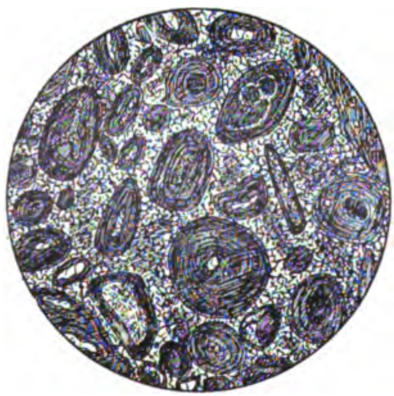

Fig. 4.

Fig. 1.—Recent Limestone, with foraminifera, calcareous algæ, shell-fragments, and crystals of olivine and augite derived from volcanic rocks, the whole united by a spicular cement. Mer, Murray Is., Torres Straits. × 12.

Fig. 2.—Carboniferous Limestone, with foraminifera and fragments of shells and crinoid-stems. Co. Carlow. × 12.

Fig. 3.—Devonian Limestone, showing septa of coral and infilling of crystalline calcite. Newton Abbot, S. Devon. × 9.

Fig. 4.—Jurassic Limestone, showing oolitic grains and crystalline cement. Trouville, France. × 12.

is improbable that filiform algæ originate oolitic grains in any case, though their adhesion may aid further deposition of calcium carbonate.

Spheroidal calcareous deposits occur in some springs, aragonite globules being thus formed at Carlsbad. These in section appear rather more uniform in structure than the ordinary oolitic grains.

With crossed nicols oolitic grains give a black cross, due either to a tangential or radial arrangement of the constituent prisms. If we can ascertain by ordinary tests that we are dealing with calcite or with aragonite, the direction of vibration for the fastest ray in the components, as given by the quartz wedge, will suffice to show in which direction the longer axes of the little prisms point (see p. 156). Thus on pushing in the wedge at 45° to the vibration-planes of the nicols, the oolitic grain will be divided into four coloured sectors shading into one another. If compensation occurs in the two sectors which lie along the longer direction of the wedge, the vibration-directions of the fastest rays are radial; if in the sectors that lie across, they are tangential. Hence we conclude as to the relations of the prisms to the spheroidal aggregate, when the grain, as is usually the case, consists of calcium carbonate.

But the common ellipsoidal type of grain gives us a quicker mode of determining this interesting point. To this matter reference has been already made when treating of aggregate polarisation (p. 149). If the elliptical section is set upright or horizontal in the field, the arms of the black cross are parallel to the vibration-planes of the nicols; if the grain is built of radial prisms, the cross is undisturbed on rotation of the stage; if, on the other hand, the components lie tangentially, as is so commonly the case, the arms approach and recede from one another during rotation.

Mr. Sorby has shown how oolitic grains recrystallise within, and form aggregates of calcite granules, all structure but the outer form being lost. The grains, probably from their being originally composed of aragonite, easily become altered, and are often stained iron-red in section, or are black with pseudomorphic infiltrations, while the groundmass of calcite granules remains clear. The oolitic ironstones of Cleveland and Northampton, where the grains consist of carbonate and oxide of iron, have been shown to result from the alteration of ordinary oolitic limestones.

Silica plays some part, however, in this series of chemical changes. On treating such ironstones with hydrochloric acid,

a very interesting skeletal residue of amorphous silica results, the forms of the oolitic grains being accurately preserved.*

Finally, the interstitial matter between the grains of oolites resembles the groundmass of ordinary limestones (Pl. I., fig. 4). It is often converted into granular calcite while the delicate structures of the grains are still preserved; but ultimately, as above hinted, even the grains may become merged into the altering groundmass. If converted, however, into ferruginous or silico-ferruginous pseudomorphs, they are likely to be preserved through immense periods of change, and will remain readily recognisable in sections.

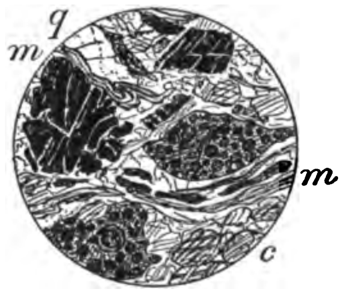

Fig. 23.—Crushed oolitic limestone passing into schist — Moûtiers-en-Tarentaise, Alps of Savoy. × 12. *c*, Calcite. *m*, Mica in elongated and contorted folia. *q*, Quartz. Traces of oolitic structure remain in some of the limestone fragments; others are compacter and almost opaque.

Dolomitic Limestones and Dolomites.—I. These resemble ordinary types; but are liable to contain cavernous hollows and cavities. The specific gravity is about 2·8. Modern coral limestone may become dolomite (see p. 203, and Skeats, *Bull. Mus. Compar. Zool. Harvard*, vol. xlii., 1903, p. 51). In older masses, the dolomite may spread as a sort of disease in bands and patches, often resembling igneous veins. The iron that is often at the same time introduced colours the dolomite a faint brown, in striking contrast with the grey limestone round it.

The well-known spheroidal aggregates in the magnesian limestone of Durham have been proved by Prof. Garwood to result from the crystallisation of calcite within the dolomitic mass (*Geol. Mag.*, 1891, p. 433).

Lemberg's test (p. 36) can be applied to the rock-surface or to the slide.

The non-effervescence of true dolomite with cold acids may cause mistakes on hurried examination.

II. The microscope shows a greater prevalence of the rhombo-

* See Judd, *Memoirs of Geol. Survey*, "Geology of Rutland," pp. 117-138; and Hudleston, "Geological History of Iron Ores," *Proc. Geol. Assoc.*, vol. xi., pp. 123, 125, &c. Fulcher, *Geol. Mag.*, 1892, p. 114.

hedron among the crystalline constituents than is the case in ordinary limestone; Lemberg's chemical test (p. 36) can be applied to the uncovered slide. (Pl. II., fig. 2.)

Brecciated Limestones.—Owing to the yielding nature of the rock, these types are fairly common where earth-movements have taken place. The cracks become filled with calcite. By development of mica along surfaces of movement, they pass over into the metamorphic "calc-schists" (fig. 23). The deformation of fossils in such rocks, or their reduction to mere mineral fragments, affords a most interesting field for observation.

Limestone-Conglomerate. See Section IX.

V. Bone-beds and Phosphatic Deposits.

The fragments of bone have usually become rich dark-brown or grey-black, and have a characteristic lustre. Associated with them is concretionary phosphate of lime, which forms nodules round them and disguises their outlines. Some phosphatic deposits consist of black casts of fossils, mingled with irregular concretionary lumps. All cases can easily be tested chemically.

"Coprolitic deposits" are often wrongly so called, consisting in reality of concretionary and septarian nodules.

When fossils have become preserved in a bed by the infiltration and segregation of phosphates, they resist ordinary physical disintegration, and are again and again found as derived fragments in formations of later periods.

VI. Rocks Deposited from Solution.

We have mentioned above the pisolitic deposit of aragonite occurring around sand-grains, &c., in some hot springs, and the oolites may also be referred to this division.

The cement of some marine limestones arises also directly from dissolved calcium carbonate, which is often deposited in needle-like crystals perpendicular to the surfaces of the other constituents.

Stalactites and Stalagmites, accumulating slowly where water emerges after passage through calcareous rocks, commonly show a crystalline structure to the eye. Other materials than calcium carbonate, such as barytes, or oxides of manganese, may occasionally be deposited in the same way. The successive layers in some stalactites, and in most stalagmites, are well

marked on broken surfaces, and the mode of deposition can be clearly appreciated from this structure.

Travertine, consisting of carbonate of lime deposited upon twigs, leaves, &c., in streams, often contains relics of vegetable matter, or casts of such materials appear when the consolidated mass is broken open. Mr. Sorby observed that even in travertine the little calcite crystals were sometimes deposited with their principal axes perpendicular to the twigs round which they formed. Travertines are characteristically pale in colour, being opaque white, brownish-grey, or slightly tinged with orange where iron oxides are more abundant.

The above deposits must be distinguished by the use of acid from the rarer but parallel siliceous forms, since the friability of many siliceous sinters prevents the estimation of their hardness with the knife.

Siliceous Sinter.—This is the deposit of some geysers and hot springs, and often forms pure white fragile crusts and stalagmitic accumulations of amorphous silica. By slow changes these pass into chalcedonic types. The siliceous sinter of geyser-basins has been stated to be deposited most rapidly where algæ are present in the water, and to be due to a direct action of these algæ (Weed, *Ninth Ann. Report U.S. Geöl. Surv.*, p. 650).

The colour of sinter passes into grey, faint brown, or even pink, as in the famous terraces of New Zealand, now destroyed.

Gypsum (Alabaster).—I. This rock is also generally white, with a compact structure, semi-transparent, and resembling some pure crystalline limestones. The glancing surfaces of the calcite cleavages in the latter are represented in some coarser alabasters by the clinopinacoidal plates of the gypsum crystals; but as a rule the mass is more compact. The hardness is only 2, and the thumb-nail thus distinguishes the two types of rock. The white powdery surfaces of gypsum when struck by the hammer resemble those of crystalline limestone.

The specific gravity is another excellent test, being only about 2·32. The rock does not effervesce with acids. In the field the whiteness of the rock, as it appears in bosses through the soil, or gleams high up among mountain-masses, is a feature that attracts attention at a distance even of miles. The comparative purity of massive gypsums prevents their weathered surfaces from being masked by products of decomposition.

II. With crossed nicols the low polarisation-colours of gypsum are seen. The crystals are granular and in contact, with well-marked cleavages.

Rock-Salt.—The characters of this rock may be seen from the

account of the mineral on p. 75. On solution in water, an earthy and often ferruginous residue is left, which may repay examination.

Some ironstones should be placed here, being earthy brown deposits formed by the oxidation of the dissolved salts of iron in the waters of lakes or bogs.

VII. Segregative and Pseudomorphic Rocks.

Concretionary Limestones.—These may be expected in the form of nodular masses in calcareous clays, often septariform—*i.e.*, cracked up subsequently and recemented by infiltrations of crystalline minerals. Fossils should be looked for in such nodules, since they may there be well preserved; often, indeed, they have given rise to the concretion by supplying a centre of the same material as that in process of segregation.

The fact that the lines of bedding pass through concretions, and are not thrust aside by their growth, shows that the action cements together the particles of the rock with a new material, or actually replaces them by a pseudomorphic product of segregation.

Cone-in-cone Structure.—This is a fairly common structure in rocks composed of carbonates, and, indeed, in any material capable of radial fibrous crystallisation. The material seems to consist of a number of funnel-shaped forms fitting into one another, some of the resulting compound cones having their apices downwards, and some upwards, in the same bed of rock. Under the microscope, films of dark impurities can be seen between the successive crystalline "funnels" composing the compound cone. The whole structure evidently results from radial fibrous crystallisation, and a struggle to get rid of the impurities amid which the crystals are developing. These become pressed in between the coats of each compound conical crystal, and allow of their separation into successive hollow cones. (See Gresley, *Geol. Mag.*, 1887, p. 17; Cole, *Min. Mag.*, vol. x., p. 136; Bonney, *ibid.*, vol. xi., p. 24).

Ironstones.—I. Many concretions consist of brown clay ironstone, which effervesces with hot hydrochloric acid, the solution becoming coloured a strong yellow. These nodules consist of carbonate of iron with brown oxide rusts. The "black-band" of the Coal-measure rocks is similar. Ironstones very frequently result from the pseudomorphosis of some ordinary sedimentary rock, though some arise from de-

position as bog iron ore, and others are merely cemented sandstones.

By the breaking up of concretionary carbonate of iron, concentric coats of limonite are formed in succession around each original centre; where the rock is split up into cuboidal blocks by jointing, each block on being broken open reveals towards the centre sections of concentric spheroidal surfaces, marked brown by the hydrated oxide, which is a stable product insoluble in water. As these surfaces approach the joint-planes, they conform more to them, and the outermost coat is often box-like and well consolidated, protecting the interior from further action. Concretionary layers of limonite, with no apparent connexion with joint-planes, may be found in many sands, and serve to protect fossils that might otherwise have been entirely dissolved.

The "pisolitic" iron-ores (more commonly "oolitic," on account of the small size of the grains) offer some points of difficulty. Some appear to owe their structure to concretionary action set up at the time of deposition of the ore, others as certainly to the pseudomorphosis of calcareous oolite. One of the most perfect and beautiful examples of this structural type of ironstone occurs near Pont de Beauvoisin in the department of the Isère. In our older examples, such as the black ironstone of Tremadoc, a dehydration has taken place, and the rock resembles a heavy compacted shale, the specific gravity readily calling attention to it. The powder is attracted by the magnet. The oolitic granules are still recognisable.

II. Concretions of siderite show a crystalline granular character (see p. 180). The oxidation and hydration of the ironstones make them fairly opaque. The "pisolitic" varieties of Wales show green oolitic grains full of granules of magnetite, the groundmass being almost opaque. The green colour may be due to silicate of iron, since a siliceous skeleton is left behind after boiling the grains in acid.*

Flint and Chert.—I. These terms can be used synonymously for the concretions and beds of chalcedonic and amorphous silica found so frequently in limestones and sandy rocks. The characteristically uniform and often conchoidal surface of fracture, the semi-transparency of fragments, and the hardness (= 7), are useful features in determination. Acids, moreover, have no effect.

Nodular flints and chert-bands are found to follow the lines of stratification of the rocks in which they occur. They may also

* Cole and Jennings, "The northern slopes of Cader Idris." *Quart. Journ. Geol. Soc.*, vol. xlv. (1889), p. 426.

be looked for in "tabular" forms along planes of jointing or faulting. In the Chalk the white exterior of the flints is due to porosity on a microscopic scale, caused by the removal of the more soluble part of the chalcedonic silica.

With the unaided eye, duller white patches are often seen in cherts and flints, which are the residue of chalk-mud, or of fossil forms, mainly sponges, about which the segregation has taken place. Fossils may be included without change, casts being formed of them, or their calcareous substance may be partly or wholly silicified, like the corals of the Portlandian in the west of England. In the Carboniferous limestone whole beds of chert occur, in which the fossils (encrinite stems, &c.) are represented by mere empty moulds, having been dissolved away subsequently to the pseudomorphic replacement of the groundmass by chalcedonic silica.

All cases of this kind deserve attention, and the knife must be kept ready to test any residual areas of carbonate of lime. By treating some of the remaining shells with acid, a partial replacement may sometimes be found to have occurred, as in the *Inoceramus*-fragments in the Chalk.

While the actual chert-substance often appears homogeneous with the lens, in many cases opaquer rod-like bodies can be detected, and these are sometimes built up into the regular meshwork of a siliceous sponge. In Chalk-flints the former spicular structure is often represented by a red-brown pseudomorph consisting of hydrated iron oxide, looking at the first glance like a mere stain running across the fractured surface.

The cherts of the Hythe sandstones of Surrey and of the Upper Greensand of the Isle of Wight are full of casts of spicules easily discernible with the lens. Many of the former include sand-grains and glauconite to an extent that makes them referable to "sandstone with siliceous cement." In some cherts, radiolaria are preserved, showing as minute dull white or grey spots on the fractured surface.

We have already seen, in discussing limestones, how original structures, lost in the mass of the rock, may be preserved in the cherts, which thus acquire additional importance. The actual origin of chert has been much discussed; but there can be little doubt that its frequent occurrence accounts for the absence in older rocks of the siliceous skeletons of radiolaria, sponges, and diatoms, such as abound in existing waters. The relation of the cherts in any formation to such traces of these organisms as remain is a matter of considerable interest.

The compact white siliceous rocks of Arkansas, called "Nova-

culites," and used as whetstones, may be allied to flint rather than to sandstone. (See Rutley, *Quart. Journ. Geol. Soc.*, vol. l, p. 377.) Much "Lydian Stone" or "Lydite" is black chert.

II. Microscopic sections show colloid, cryptocrystalline, and crystalline silica often in the same slide, the crossed nicols proving that the general structure is chalcedonic. The polarisation-effects are thus speckly, the general tints of the field being grey during rotation unless much quartz has been developed. Dr. Hinde* has described globules of colloid silica, about ·02 mm. in diameter (which from their forms are not silicified coccoliths), occurring in many of the sponge-beds that he has examined. The chalcedony also produces globular aggregates, giving black crosses between the nicols. The spicules of sponges are rarely preserved as colloid silica, but sometimes remain as aggregates of the little globules. Chalcedonic silica partly or wholly replaces them, and frequently glauconite fills the canals and is left as a cast after their complete removal. Sometimes the spicule itself is replaced by glauconite. Radiolaria may be present, often as mere colourless circular areas of chalcedony, but showing, in fortunate sections, their reticulated mesh, or an inner globe supported within an outer one.

The traces of foraminifera, shell-fragments, and indeed all the structure of the adjacent limestone, preserved in chalcedonic silica, as may be seen in sections of certain flints, are good evidence of the actual pseudomorphosis that has occurred. The section should be cleaned from balsam and treated with acid to prove that the walls of the foraminifera, &c., have been truly replaced by silica.

Similarly, the oolitic structure may be seen in flint, and must not be mistaken for the outlines of unicellular organisms.

Phosphatic Concretions, which generally appear rich brown in sections, have been touched on in division V. of this chapter.

VIII. Vegetable Deposits.

If we exclude anthracite, the characters of the coals that serve readily in their recognition are their very low specific gravity, their hardness of about 2, and their combustibility.

Brown coal is a lignitic coal, sometimes laminated, of a warm brown colour. It is sectile and sometimes clayey, and does not soil the fingers.

Common coal needs no description as to external characters. Its

* "On beds of sponge-remains in the south of England." *Phil. Trans.*, part ii., 1885, p. 427, and plate 40.

specific gravity is about 1·28, and it is also sectile. In some beds small black or brown disc-like bodies can be seen projecting from the fractured surfaces, and lying in the planes of bedding. These are the compressed macrospores of the lycopodiaceous plants that flourished in the Carboniferous period, and appear in microscopic sections, taken across the bedding, as transparent orange elliptical structures, while the opaque carbonaceous groundmass is full of similarly coloured remnants of minuter spores. When cut parallel to the bedding, the circular form of the macrospores is seen.

Anthracite has a more brilliant lustre, does not soil the fingers, is more brittle, and has a specific gravity near 1·4. Its hardness may reach even 5, and it is difficult to burn before the blowpipe.

To study the organic remains that have given rise to coals, we must examine the adjacent shales and sandstones, where the plants have been more isolated and not matted together into an indistinguishable mass. Similarly leaf-beds are not the best preservers of fossil leaves; but exquisite examples may be found in the same series of deposits by a search among the underlying or overlying muds.

Diatomaceous deposits are friable light-coloured masses found in some lakes and also formed, in less purity, upon sea-floors. The delicate frustules of the diatoms, transparent and without effect on polarised light, must be studied microscopically with high powers. The rock, it may be noted, does not effervesce with acids. Fossil deposits of this kind are rare, through the destruction of the frustules by solution.

We have referred on p. 203 to the calcareous deposits formed by corallines (nullipore-deposits), and on pp. 204 and 208 to the possible direct algal origin of oolitic limestone and siliceous sinter.

IX. Mixed Coarse Fragmental Deposits.

Gravels, Pebble-Gravels, and Conglomerates.—The remarks made on grits and sandstones are applicable to these coarser rocks. The size of the constituent rock-fragments should be ascertained, as well as the degree of rounding. Considerable variety in the nature of the constituents is to be expected in these accumulations in mountain-streams or on coarse beaches, since the materials have travelled a comparatively short distance, and the weaker members have been often fortunately preserved from further trituration. Thus the magnificent

Nagelflüh accumulations that accompanied the earlier development of the Alpine chain contain a rich store of rocks from the ridges then raised above the sea, some of the most interesting beds being composed of pebbles of compact grey limestone. The red conglomerates, again, that fringe the E. Devon coast preserve for us abundant relics of the volcanoes that were built up around Dartmoor in early Mesozoic times, of which in most cases only the deep-seated portions remain *in situ*. (Compare fig. 44.)

The alteration of rocks in loose gravels easily permeable by water often makes collecting unsatisfactory, and warns one that the solid old conglomerates may not always tell us the whole truth. Thus on the Surrey Downs white soft bodies occur in late Tertiary gravels; these resemble chalk and can readily be used for writing on a blackboard. But they contain no appreciable quantity of calcium carbonate, and are in reality completely broken down flint pebbles, rendered opaque white, like the surfaces of flints in chalk, by the dissolving away of a large amount of silica.

Limestone pebbles of considerable size may undergo solution in permeable gravels, leaving only light and porous clayey residues, which fall to pieces when pressed between the fingers.

The examination of rock-fragments in these coarse accumulations, in the hope of obtaining fossils, requires patience, but is in the end a fruitful study. The flints so widely scattered in Britain contain abundant casts of Cretaceous fossils, thus proving their origin; and the Silurian forms in the Triassic pebble-beds of Budleigh Salterton have been the subject of memorable investigations.

The nature of the cementing material of conglomerates is always of interest, and the production of hard rocks by the deposition of calcium carbonate, or by the oxidation of dissolved salts of iron, in recent gravels is well known to workers among our glacial or our beach deposits. Such rocks, following Mr. Lamplugh's suggestion,* may conveniently be called **calcicrete** and **ferricrete** respectively.

* *Geol. Mag.*, 1902, p. 575. Mr. Lamplugh writes "calcrete"; Prof. Bonney prefers calcicrete.

CHAPTER XIX.

IGNEOUS ROCKS.

THE study of the igneous rocks has become unfortunately so involved in the question of their nomenclature, that it is impossible to give an outline of the characters employed in their discrimination without a statement of the sense in which each particular name is used. All these names represent groups of rocks graduating into one another. When a rock is on the border-line between two groups, whether in structure or mineral constitution, we must be content to say so, without attempting to disguise natural facts by our classification. Petrography has of late suffered from the introduction of an abundance of new terms, and, what is far worse, of old terms defined in new senses; but the majority of these can be avoided by the use of familiar adjectives or mineral prefixes, to the great lightening of the science.*

All workers will agree that it is of advantage to use certain broad general names for the rock-types ordinarily met with. How far definition should go beyond this hand in hand with chemical analysis is a matter open to discussion. To the majority of geologists, the precise chemical composition of a rock, and especially of a rock-specimen, can never seem more than the result of local accidents. The tracing out of these accidents, in order to gain an idea of the history of the mass, is of course enormously facilitated by a series of analyses of well chosen material. Here the field-observer at once possesses his great advantage. He collects from all portions of the mass in question, notes its variation from point to point, observes any tendency to segregation that may have occurred during cooling, and reconciles appearances and structures that would have seemed contradictory in isolated specimens. (See Teall, *Natural Science*, vol. i., p. 297.)

The following-out thus of an igneous rock in the field is a most important lesson, and will soon determine what is valuable and what is valueless in any proposed scheme of classification. Next to the variations in the mass itself, come its relations to its surroundings, and here the geological agents conspire again and again to baffle the observer. On sea-coasts the bare exposures occasionally equal in clearness the well-known text-

* On the classification of igneous rocks, see A. Harker, *Sci. Progress*, vol. iv. (1895-6), p. 469; Lœwinsson-Lessing, "Studien über die Eruptivgesteine," *Compte rendu, Congrès géol. internat.*, St. Petersbourg, 1897, pp. 193-464; and, from the chemical point of view, Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks*, Chicago, 1903.

book diagrams; but on grassy slopes, or the high taluses above them, the junctions of an igneous rock with other masses are exceedingly likely to be obscured. The difference of hardness and consistency that commonly exists tends, moreover, to produce faulted junctions where igneous rocks abut on sedimentary; breccias of the latter or of both arise, and the intrusive veins or the products of contact-metamorphism, which might have told so much, are disappointingly broken away and rendered useless. This perhaps makes the search among our older areas the more absorbing; but unquestionably study should commence among Tertiary volcanoes, where denudation has exposed the various masses without destroying their continuity and connexions.

Although the actual margin, the selvage, of an igneous rock is likely to be much decomposed, yet specimens should always be collected from it, since here lies often the only chance of obtaining glassy or partly glassy products. As we pass inwards, the more crystalline types of rock are met with. At the same time the specific gravity of our samples rises; and that of the most crystalline type will give a fair notion of the silica-percentage of the mass. Here we must be on the look-out for the included foreign masses that often occur in crystalline rocks. If such patches are numerous, we must take them into account when discussing the composition of the igneous mass. It will be interesting to trace how far the igneous rock has become modified by the complete absorption of foreign matter as it moved forward. It is highly probable that the igneous rocks of the inner layers of the earth's crust are of simpler composition than those that we meet with in the outer layers, and that the latter owe many of their characters to repeated intermixture. Quartz-rock, orthoclase-rock, &c., are admissible as simple types of igneous rock. Iron-nickel-rock, a still simpler type, is already familiar to us in meteorites.

Igneous rocks may be broadly divided into holocrystalline on the one hand, and partly or wholly glassy types on the other. They cannot be classified according to their mode of occurrence, since a thin dyke, cooling quickly through the contact-rocks, may reproduce all the features of a glassy lava-flow; while the central parts of a thick mass of lava may become ultimately holocrystalline. It may reasonably be concluded, however, that a coarsely crystalline specimen has come from some source originally deep-seated; beyond this the appearance of hand-specimens may be deceptive, since even the scoriaceous structure, often insisted on as a character of lava-flows, is again and again found in intrusive sheets or dykes.

Of course cases must occur where minute traces of glassy

matter remain which can only be detected in thin sections; on the other hand, the compact and lava-like groundmass of some rocks may prove to be completely crystalline under the microscope. By Cordier's method of the examination of a powdered rock under the microscope, the intimate structure of the groundmass can often be better determined than in a thin section, the translucent and smaller fragments being of course selected.

The further classification rests on a combination of mineralogical and chemical considerations. The comparison of analyses has been immensely aided by the work of the United States Geological Survey (see especially *Professional Papers*, No. 14, 1903, and No. 28, 1904).

The broad names here used are those that seem best founded; and most of them possess a historic attraction in addition. The divisions I. and II. refer as before to megascopic and microscopic observations respectively.

A. Holocrystalline Rocks.

I. Granite and Eurite Group.

These are the typical acid holocrystalline rocks, there being an excess of silica, which manifests itself as free quartz, though often on a microscopic scale.

Granite. *Structure*—Granitic. *Constituents*—1, Quartz; 2, Orthoclase or Microcline; 3, Mica or Amphibole. Rarely Pyroxene. Commonly some Albite or Oligoclase.

I. The clear glassy granules of the quartz, devoid of cleavage, are easily distinguished; muscovite may be present, though rarer than dark micas; the dull edges of biotite crystals often resemble fibrous hornblende, but the lustre of the basal planes will easily serve to identify them.

The prevalence of potash-felspar may be determined by the flame-test. The simple twinning of orthoclase will often be fully apparent on particular surfaces of the rock, and not on others, owing to the position adopted by the large and somewhat tabular crystals, which lie with their clinopinacoids in planes fairly parallel to one another. Oligoclase may always be expected, and the potash-felspar may contain much soda.

Specific Gravity.—Rather above 2·65.

Typical Analyses.—A. Doocharry Bridge, Co. Donegal. Haughton, *Trans. R. I. Acad.*, vol. xxiv. (1871), p. 220.

B. Gready, Cornwall. Light and dark Micas. J. A. Phillips, *Quart. Journ. Geol. Soc.*, vol. xxxvi. (1880), p. 8.

C. Syene, Egypt. With Oligoclase, dark Mica, and some Hornblende. Scheerer, 1866, quoted in Roth's *Beiträge zur Petrographie*, 1869, p. xlvi.

	A.	B.	C.
SiO_2	72·24	69·64	69·95
Al_2O_3	14·92	17·35	13·32
Fe_2O_3	1·63	1·04	...
FeO	0·23	1·97	4·90
MnO	0·32	trace	...
CaO	1·68	1·40	1·79
MgO	0·36	0·21	0·66
K_2O	5·10	4·08	3·47
Na_2O	3·51	3·51	3·31
H_2O	...	0·72	1·27
TiO_2	...	...	0·95
	99·99	99·92	99·62

II. While the general appearance of the constituents under the microscope is irregular and allotriomorphic, the felspars often preserve their prismatic forms, and the mica and hornblende show still better traces of bounding planes. The quartz is, however, granular, and commonly abounds in liquid enclosures. The ground may be composed of micropegmatitic quartz and felspar.

Fig. 24. — Granite. Near Dublin. × 12. *b*, Dark Mica, with deep brown patches included. *m*, Muscovite. Near the top of the field a hexagonal (basal) section occurs. *o*, Orthoclase. *q*, Quartz.

Two or three sections may be required to determine the relative proportions of potash-felspar and soda-lime varieties. A large series of rocks known familiarly as granites must be passed over to the quartz-diorites, having, indeed, but little potash in their composition, together with a deficiency in silica. Where muscovite is present, orthoclase may naturally be expected to be predominant.

Magnetite is not conspicuous. Zircon and apatite are common, as minerals of early development in the rock; the minute prisms of zircon are best seen where included in the micas. Sphene and garnet are frequent accessories. By alteration, tourmaline and topaz come in, the former replacing various silicates, and the latter representing in particular the felspars. Fluor-spar and secondary quartz, often with good outlines, accompany these changes.

Varieties of Granite.—GRANITE WITH MUCH PLAGIOCLASE, and with biotite or hornblende. This is the "Granitite" of G. Rose; Rosenbusch, however, uses "granitite" for any biotite-granite. See analysis C.

TOURMALINE-GRANITE.—The smaller constituents become entirely replaced by tourmaline, blue or brown in section, and by secondary quartz, the porphyritic felspars often remaining only slightly attacked. The Cornish "Luxulyanite" is one variety of such altered granites, and quartz-schorl-rock is a final stage.

GREISEN is a somewhat uncommon ally of granite, in which felspar is absent. Topaz, however, abounds in the typical rock from Zinnwald, Saxony, and probably represents altered aluminous silicates. The other constituents are quartz and a pale mica, often a lithia-bearing species.

APLITE (Retz; more correctly HAPLITE; ALASKITE of Spurr, *20th Ann. Rep. U.S. Survey,* p. 189).—Practically composed of quartz and orthoclase only. Commonly pale in colour and fine-grained; often micropegmatitic. Flakes of muscovite glimmer here and there. Occurs often as veins in granite, and even forms considerable rock-masses. The silica rises to at least 76 per cent.

GRAPHIC GRANITE (PEGMATITE of Haüy *).—The later and erroneous extension of Haüy's term to any coarse muscovite-granite occurring in veins necessitates a return to the descriptive name "graphic granite." I. The rock is commonly a coarse aplite, mica occurring here and there in nests and bunches, being excluded from the parts that exhibit the typical structure. To the eye the continuous cleavages of the felspar are easily apparent, the quartz being apparently in detached fragments resembling eastern characters, embedded in the more opaque felspar (πήγματα). Sometimes hand-specimens of the rock cleave as if composed merely of coarsely developed felspar. The lens often shows a microcline structure.

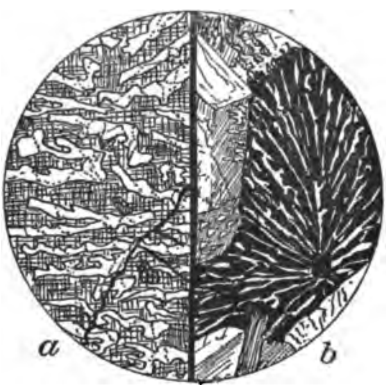

Fig. 25.—*a*, Graphic Granite. Vein in Stanner Rock, Herefordshire. × 8. *Nicols crossed.* Clear quartz; microcline with characteristic twinning. *b*, Micropegmatitic intergrowth of quartz and felspar, in Eurite. Stanner Rock, Herefordshire. × 160. *Nicols crossed.* The felspar is in a position of extinction. Other micropegmatitic areas and felspar crystals lie around.

II. The felspar is usually microcline, showing the cross-twinning (fig. 25, *a*); the section should be thinly ground. The quartz

* *Traité de Minéralogie,* 2nde édit., tome iv., p. 436.

between crossed nicols appears optically continuous over considerable areas, being in fact intergrown in large crystals with the felspar. The hook-like forms of the quartz come out distinctly if the surrounding felspar is placed in a position of extinction.

ORBICULAR GRANITE.—A rare form, in which the minerals are grouped into bold crystalline spheroidal aggregates, usually coated outwardly with dark mica.* The relations of the spheroidal part to the mass of the granite, and any facts bearing on the origin of the structure, should be carefully noted in the field.

Eurite.—This name, given by d'Aubuisson † in 1819, seems to cover admirably by its original definition the fine-grained and compact forms of granite, known commonly in England as "Quartz-Felsite" and on the Continent as "Microgranulite," "Quartz-Porphyry," &c. The old "petrosilex" and most of the "compact felspars" and "hornstones" must come under eurite; also the Cornish "elvans" or "elvanites." "Felsite" is so loosely defined by its originator, and is so differently used by different writers, that its reputation as a rock-name is lost.

It must be remembered that the "quartz-porphyries" of the Continent are in large part altered rhyolites; those divisions described by Rosenbusch as "microgranites" and "granophyres" correspond, however, to eurite.

Structure.—Essentially compact in appearance, and microgranitic with the lens. Commonly with porphyritic orthoclase and quartz. *Constituents*—Like granite.

I. Colour pale as a rule, but occasionally deep grey or red-brown. Commonly yellowish or pinkish-brown, or pale grey. The knife scratches fresh specimens with difficulty, and the most compact varieties resemble flint. The joints are clean, and the surfaces often have hard white decomposition-crusts. Without the microscope it is impossible to separate hand-specimens of true eurites from acid lavas that have become holocrystalline by secondary devitrification.

The porphyritic quartz that is so often seen is a good guide as to the highly siliceous character of the rock. It sometimes occurs in well-bounded double pyramids with a short prism, as in the rock of Auersberg in the Harz. Tourmaline appears sometimes in radial nests as a secondary product.

* For an account of one of these rocks see F. H. Hatch, "On the spheroid-bearing granite of Mullaghderg," *Quart. Journ. Geol. Soc.*, vol. xliv. (1888), p. 548.

† *Traité de Geognosie*, tome ii., p. 117.

Specific Gravity.—About 2·65.

Typical Analyses.—Theoretically, every granite should have its corresponding eurite. The proportion of soda often links these rocks with the quartz-aphanites.

A. Fine-grained "Elvan," Mellanear, Cornwall. J. A. Phillips, *Quart. Journ. Geol. Soc.*, vol. xxxi. (1875), p. 335. Mica.

B. Quartz-porphyry, Triberg, Baden. G. H. Williams, *Neues Jahrb. für Min. &c.*, Beilage Bd. ii. (1883), p. 609.

C. Soda-Eurite. Llyn-y-Gader, Cader Idris. Holland, *Quart. Journ. Geol. Soc.*, 1889, p. 435.

	A.	B.	C.
SiO_2	71·46	77·68	72·79
Al_2O_3	15·38	12·95	13·77
Fe_2O_3	0·30	0·96	3·32
FeO	2·27	0·37	...
MnO	trace	...	trace
CaO	0.47	0·30	1·94
MgO	0·22	0·21	0·62
K_2O	5·51	4·37	2·99
Na_2O	2·79	3·18	4·12
H_2O	1·70	0·71	1·08
	100·10	100·73	100·63

II. The groundmass is micrognanitic and often micropegmatitic. The quartz and felspar are not unfrequently grouped in micropegmatitic intergrowths of spherulitic form around the porphyritic crystals ("granophyre" of Rosenbusch)—fig. 25, *b*. All stages appear to exist between these aggregations and spherulites with rays composed of crystalline fibres. Some types of altered spherulites in devitrified lavas are, again, indistinguishable from these holocrystalline aggregates in the compacter eurites; but, as a rule, the structures are distinct. Careful observation will show that where such an aggregate-growth occurs round a quartz crystal, the quartz of the micropegmatite is in optical continuity with that of the crystal.

The porphyritic crystals, even of quartz, are often well bounded, though sometimes cracked and broken by movement, or corroded by the molten ground. A fluidal structure is occasionally set up.

The ferro-magnesian constituent is commonly biotite, often giving wisp-like yellowish sections. Muscovite occurs in many Cornish "elvans," and forms at times little fan-like bunches;

but neither mineral is prominent, and the rock has a marked aplitic tendency.

Varieties of Eurite.—EURITE RICH IN SODA (SODA-EURITE). This includes very many of the micropegmatitic types above referred to; many of the porphyritic felspars are albite or oligoclase, and the rock is linked thus with the quartz-aphanites. Rosenbusch's "Quartz-Keratophyres" come here. See analysis C.

II. SYENITE AND COMPACT SYENITE GROUP.

The complete or almost complete absence of free quartz, and the predominance of orthoclase, are the distinctive characters of this group.

Syenite (Werner). — *Structure* — Granitic. *Constituents* — 1, Orthoclase, or other potash felspar; 2, Amphibole, Pyroxene (usually ægirine), or Mica. Commonly some quartz; also albite or oligoclase.

I. This rock is rare as compared with granite and quartz-diorite, and it must often be a matter of opinion as to how much quartz is permissible in a true syenite. With the older writers the term was synonymous with hornblende-granite.

The Mica-Syenites (or "Minettes") contain biotite, often in abundance, and the dark lustrous plates conceal the felspar in the fine-grained varieties, so that the flame-test or the microscope must be brought to bear to distinguish the rock from mica-diorite.

Sphene may often be recognised, occurring as small hard yellow crystals.

Specific Gravity.—About 2·75 or somewhat higher.

Typical Analyses.—A. Hornblende-Syenite. Plauenscher Grund, Dresden. Zirkel, *Poggend. Annalen*, 1864, p. 622. Typical rock of Werner.

B. Hornblende-Syenite. Follmersdorf, Silesia. H. Traube, *Neues Jahrb.*, 1890, Bd. i., p. 212. Specific gravity, 2·86.

C. Elæolite-Syenite. Litchfield, Maine. *Bull. U.S. Geol. Surv.*, No. 148, p. 65. With mica and sodalite.

	A.	B.	C.
SiO_2	59·83	65·63	60·39
Al_2O_3	16·85	13·85	22·57
Fe_2O_3	...	2·02	0·42
FeO	7·01	2·80	2·26
MnO	...	trace	0·08
CaO	4·43	3·43	0·32
MgO	2·61	2·79	0·13
K_2O	6·57	6·25	4·77
Na_2O	2·44	1·84	8·44
Loss on ignition,	1·29	1·17	0·57
	101·03	99·78	99·95

II. Similar to granite, but the quartz must be insignificant or absent. In some cases traces of pyroxene remain, the hornblende having arisen by paramorphic change; these residual crystals appear as pale and usually greenish areas surrounded by irregular zones of hornblende. Rocks consisting entirely of augite and orthoclase, though certainly rare, must be classed as Augite-Syenite, and such masses probably underlie many trachytic volcanic areas, being altered into ordinary hornblendic types by the time that they are exposed by earth-movement and denudation.

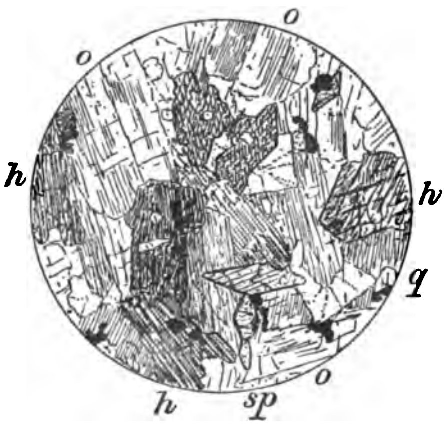

Fig. 26.—Syenite. Plauenscher Grund, Dresden. × 8. *h*, Green hornblende. *o*, Orthoclase, fairly prismatic in habit. *q*, Accessory interstitial quartz. *sp*, Sphene, marked out by its high refractive index and lozenge-shaped sections.

Zircon and sphene are particularly common in syenites.

Varieties of Syenite.—Nepheline-Syenite (Elæolite-Syenite).

I. The nepheline, in the coarse elæolite form, resembles brownish or greenish quartz, but may be distinguished by the knife. The varieties with hornblende have been called "Foyaite" from Foya in Algarve, and those with mica "Miascite" from Miask in the Urals; but the well-known examples from the Bamle area are rich in soda-pyroxene. Zircon is common, and forms large yellow crystals in the coarse biotite-nepheline-syenite of Miask. Blue sodalite occurs in a Transylvanian variety ("Ditroite"), and in a similar rock in the Ice River Valley, Canadian Rocky Mountains.

A type allied to these rocks, but of distinctly basic character, has been described by Prof. Lawson as "Malignite" (*Bull. Geol., Univ. of California,* vol. i., p. 337); it consists of nepheline, soda-pyroxene, and apatite, with orthoclase enclosing them ophitically. Lawson regards this rock as the plutonic repre-

sentative of the leucitites of Vesuvius; in both the silica is about 48 per cent.

II. Some practice, and the observation of the uniaxial figure with convergent light, is needed to detect the irregular grains of nepheline (elæolite) in these granitic rocks. The felspars often show a microcline structure, and are sodic types. Soda-lime felspars are common. The ferro-magnesian silicates are interesting, being, in addition to biotite, forms of soda-amphibole and soda-pyroxene, the former being rich dark-brown or green and highly pleochroic, approaching arfvedsonite, while the latter, distinguished by its cleavages, approaches ægirine, and is green and less pleochroic.

Compact Syenite.—We may use this name for the fine-grained types corresponding to eurite, in the absence of any well-defined term. The "Orthophyre" of Coquand* comes partly here, partly with eurite; also many "felsites." "Orthoclase-porphyry" has been used for porphyritic forms.

Structure.—Microgranitic or microcrystalline. Sometimes with porphyritic orthoclase. *Constituents*—Like syenite.

I. These rocks are difficult to distinguish from eurite with the eye, though more yielding to the knife. Colour commonly reddish or pinkish in the varieties rich in felspar. Many "Mica-traps" come here, which are dark with lustrous mica; these are the compacter "Minettes," and they pass into a group too poor in silica to be included under Syenite. This outlying group, with many of Rosenbusch's "Vogesites" (see below), comes under the "Lamprophyres" of that author.

Specific Gravity.—2·7, but higher in the varieties rich in biotite, and approaching 2·8.

II. Quartz must be carefully sought for and found practically wanting. The alteration of the felspars in many examples, such as the compact mica-syenites, makes even microscopic determination difficult; but the flame test will give an idea of the amount of potash present.

The absence of free silica prevents the development of micropegmatitic and the so-called "granophyric" structures, such as are common in the eurites.

The porphyritic orthoclase crystals, which are characteristic, often preserve their outlines well.

Varieties of Compact Syenite.—Rosenbusch terms the varieties rich in soda "Keratophyre." Those with hornblende or pyroxene

* *Traité des Roches*, 1857, p. 65.

form his "Vogesite." Varieties with a felspathoid, intermediate between felspathoid-syenite and phonolite, have been styled "Tinguaite." The nepheline in a red rock from the Val Fiemme near Predazzo is porphyritic, and, though altered, shows its characteristic outlines.

III. Quartz-Diorite and Quartz-Aphanite Group:

In this group of very common rocks, usually styled simply "diorites," there is free silica in the form of quartz; but the fact that the felspar is oligoclase or even labradorite keeps the total silica-percentage below that of the granites. They come thus at the head of Prof. Judd's *Intermediate Igneous Rocks.*

Quartz-Diorite.—*Structure*—Granitic. *Constituents*—1, Quartz; 2, Plagioclase; 3, Amphibole, Pyroxene, or Mica.

I. An immense number of the "granites" of commerce come under this head. The striation of the plagioclase and the absence of the twinning of orthoclase are noticeable with the lens. Otherwise these rocks resemble granite. The colour is generally grey, but red felspars may occur. The remarks made on the mica-syenites apply equally to the fine-grained Mica-Diorites, which mostly contain quartz. Dark-coloured quartz-mica-diorites from the neighbourhood of Brest have been named "Kersanton," after a village so-called, and Delesse employed "Kersantite" for varieties with amphibole or pyroxene in addition to mica, the types occurring in the Vosges.

"Tonalite" (vom Rath, after Monte Tonale in Western Tyrol) is a quartz-biotite-diorite in which the minerals are well developed, the white felspar contrasting boldly with the dark bronze-coloured mica.

There is no doubt that masses of quartz-diorite arise as products of admixture where granite intrudes into more basic masses. Any pyroxene in the latter is then liable to recrystallise in the new joint rock as hornblende.

Specific Gravity.—Approaching 2·85 or even 2·9.

Typical Analyses.—The silica-percentage has been commented on above, these rocks falling short of the typical "acid" group.

A. "Tonalite," Adamello Range, Tyrol. Vom Rath, *Zeitsch. d. deutsch. Geol. Gesell.*, 1864, p. 257. Much Quartz. Both Hornblende and Biotite.

B. Quartz-Pyroxene-Diorite, Vildarthal, Tyrol. Teller & von John, *Jahrb. d. Geol. Reichsanstalt*, 1882, p. 589. Enstatite and Augite.

	A.	B.
SiO_2	66·91	59·97
Al_2O_3	15·20	16·93
Fe_2O_3	...	2·41
FeO	6·45	4·83
CaO	3·73	5·10
MgO	2·35	3·61
K_2O	0·86	1·32
Na_2O	3·33	3·87
Loss on ignition	0·16	1·60
	98·99	99·64

II. The microscopic features of granite recur here, with plagioclase (commonly oligoclase) in place of orthoclase. The greater number of so-called "hornblende-granites" must be placed as quartz-hornblende-diorite when viewed in section. Where the hornblende can be shown to have arisen from pyroxene, the rocks are sometimes classed as "Epidiorite," and in these cases the quartz is very likely of secondary origin. The fibrous irregular nature of the secondary amphibole will often distinguish epidiorite from true quartz-diorite.

The typical "epidiorites" show a schistose structure in section; the felspar is granular; the hornblende is sometimes fibrous and actinolitic, sometimes also granular. Residual pyroxene of paler colour may occur.

Though pale augite may be expected in quartz-diorite, in marked contrast to the richly coloured amphiboles and micas, yet rhombic pyroxene is rare.

Sphene and apatite are common; and magnetite and titanic iron assume importance as the proportion of silica diminishes.

Quartz-Aphanite.—This series includes almost all the compact hornblende-diorites or Aphanites of Haüy. See Aphanite.

Structure.—Microgranitic or microcrystalline, the felspars being occasionally rod-shaped and the structure approaching that of dolerite. *Constituents*—Like quartz-diorite.

I. The quartz may be barely visible, though widely disseminated. Dark green fibrous hornblende, or abundant flakes of mica, may render the rock almost black, and in the hand it may with fairness be mistaken for dolerite. Many quartz-aphanites are, indeed, altered dolerites, and would be styled by various authors "fine-grained epidiorites" or "quartz-hornblende-diabases." The micaceous varieties include many fine-grained "kersantites."

Specific Gravity.—About 2·85.

II. Plagioclase and quartz, the important distinguishing

minerals, must be looked for. They may be found in micropegmatitic intergrowths, sometimes globular, as in the eurites. Some of the rocks styled "granophyre" must come over to this division. In the more basic types pyroxene is common.

It is impossible to make any microscopic distinction between the quartz-aphanites and many "fine-grained quartz-diabases." The quartz in the latter, however, is sometimes clearly secondary, occurring in strings and veinules.

IV. Diorite and Aphanite Group.

The supposed importance of distinguishing rocks containing amphibole from those containing pyroxene led to a double nomenclature in this group; but the corresponding lavas, the andesites, were for the most part investigated at a later period, and were arranged under one common name. The pyroxenic "gabbros" and "dolerites" pass, again and again, into amphibolic "diorites" and "aphanites" by paramorphic changes, and these types cannot be legitimately divided. The limits of the group, however, must, as in other cases, be chemical rather than purely mineralogical, and many "hornblende-gabbros" without olivine may have only 45 per cent. of silica, and are more basic than some members of the "olivine-gabbro" group (see Brögger, *Gesteine der Grorudit-Serie*, 1894, p. 93).

Diorite (*Haüy*,* quoted by d'Aubuisson in 1819, from διορίζω, "I distinguish," indicating the distinctness of the typical minerals, hornblende and felspar), **Gabbro** in part. *Structure*—Granitic to ophitic. *Constituents*—1. Plagioclase (commonly Oligoclase or Labradorite); 2, Amphibole, Pyroxene, or Mica.

I. Quartz must be practically absent. Hornblende and biotite will commonly be found side by side; some quartzless "kersantites" come here. The Gabbros (Pyroxene-Diorites) contain augite or diallage, and sometimes enstatite ("Norites"), these minerals often enclosing the prismatic felspars ophitically. The rock called "Gabbro" (*von Buch*) or "Euphotide" (*Haüy*) consists typically of diallage and plagioclase, and may be regarded as falling in this group when it contains 50 per cent. of silica or more. The olivine which usually marks the basic varieties is often difficult to recognise in the field.

The lime-soda felspars of the pyroxene-diorites (gabbros) easily become opaque and dull, passing into the saussuritic condition. Amphibole developes in the diallage, which often becomes green, as in the ornamental stone, "Verde di Corsica," and in a

* *Traité de Min.*, 2. éd. (1822), tome iv., p. 540. The rock was distinguished from syenite by Haüy only by its smaller proportion of "felspar."

similar gabbro near Saas. Besides passing into diallage, the augite sometimes developes the three series of schiller-planes that produce the dark lustrous "pseudo-hypersthene" variety. This was naturally often described as hypersthene by the older writers, so that the rocks called "Hypersthenite" must now be accepted with the utmost caution and submitted to microscopic tests. A pyroxene-diorite passing into the "epidiorite" state commonly shows patches of grey-green silky matter, due to the actinolitic amphibole.

Specific Gravity.—From about 2·85 to 3·0.

Typical Analyses.—A. Hornblende-Biotite-Diorite. Unalaska Island, Alaska. Hillebrand, *Bull. U.S. Geol. Surv.*, No. 168 (1900), p. 226.

B. Hornblende-Augite-Diorite. Near Inchnadampf, Sutherland. Teall, *British Petrography*, p. 265.

C. Gabbro. White Face Mountain, New York. Steiger, *Bull. U.S. Geol. Surv.*, No. 168 (1900), p. 36. Labradorite, augite, hornblende.

	A.	B.	C.
SiO_2	58·63	52·47	53·18
Al_2O_3	16·23	12·15	23·25
Fe_2O_3	1·91	3·47	1·53
FeO	4·20	5·23	1·82
CaO	6·59	9·71	11·18
MgO	4·28	9·94	2·60
K_2O	2·09	2·26	0·86
Na_2O	3·51	2·81	3·97
H_2O	1·32	1·62	1·13
TiO_2	0·74	CO_2 0·54	TiO_2 0·45
Other substances	0·43	...	0·54
	99·93	100·20	100·51

II. Many hornblende- and mica-diorites, when submitted to the microscope, have to be handed over to the quartz-diorite group. The conditions that produce hornblende and quartz are to some extent similar, since neither mineral results experimentally from mere dry fusion. On the other hand, the pyroxene-diorites are found free from quartz, and give rise to true diorites by paramorphic change.

In the Pyroxene-Diorites (Gabbros) the plagioclase is oligoclase or labradorite, frequently the latter. The saussuritic products within the felspars occasionally make the sections dull and nearly opaque. The passage from augite to diallage may be noted, and amphibole appears on the edges of the altering pyroxenes, or sporadically within them. A good deal of chlorite occurs between the constituents; this arises from the alteration of the ferro-magnesian minerals.

Magnetite and titanic iron ore are prominently seen. Epidote is a common alteration-product in the diorites, owing to the large proportion of lime present (compare fig. 29).

Among the pyroxene-diorites the ophitic structure is common. The felspar is well bounded and lies at random in the field, and the pyroxene has settled down round it, filling up the interstices, and forming crystals of considerable size. Thus the pyroxene areas will be found between crossed nicols to be optically continuous over a large portion of the section, and the consistent direction of their cleavages will point to the same conclusion. Though often called "ophitic plates," it must be remembered that such developments of pyroxene occur in three dimensions and are not limited by the thickness of the slide.

Varieties of Diorite.—Nepheline-Diorite (Elæolite-Diorite; "Theralite" of Rosenbusch). A rare rock corresponding to the

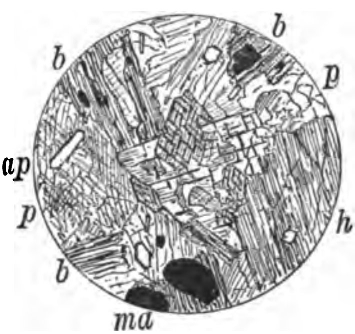

Fig. 27.—Altered Pyroxene-Mica-Diorite. Stanner Rock, Herefordshire. × 12. *ap*, Hexagonal and other sections of apatite included in the other minerals. *b*, Biotite. *h*, Green fibrous hornblende, occasionally in well marked crystals, developing at the expense of augite. *ma*, Magnetite. *p*, Plagioclase much altered. In the centre of the field is a pale crystal of original augite, with rectangular cleavage-cracks. Hornblende is developing in this by paramorphic change.

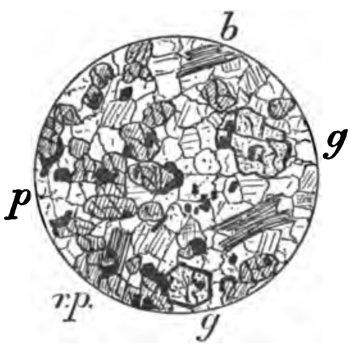

Fig. 28.—Granular Pyroxene-Diorite. Near Huntly, Aberdeen. × 35. *b*, Biotite. *g*, Garnet, noticeable by its high refractive index. *p*, Plagioclase in irregular grains of approximately equal size. *r.p*, Rhombic pyroxene (hypersthene).

nepheline-syenites; the deep-seated representative of the nepheline-andesites or "tephrites."

Granular Diorite.—A number of "epidiorites" are granular,

as described under quartz-diorite; the felspar in these forms a mosaic, and is often a product of recrystallisation. In addition, there are some remarkable pyroxene-diorites in which the minerals are of granular form and unusually clear and fresh in sections. The minerals are, perhaps, all of secondary origin, when these rocks are associated, as they often are, with schists.

The minerals are commonly plagioclase, green monoclinic pyroxene, hypersthene or amblystegite, magnetite, and often garnet. The last-named must be distinguished by its isotropism from the hypersthene, the pink colour being the same in many sections. These rocks are often aphanitic, and have very probably a composite origin. They are further discussed on p. 286.

Aphanite (*Haüy*,* 1822, from ἀφανίζομαι, "I disappear," indicating the indistinctness of the constituents in opposition to those of the coarse-grained diorites). **Dolerite** (*Haüy*, † 1822, from δολερός, "deceitful") in part.

This group includes many "Porphyrites," and the quartzless plagioclastic members of the "Lamprophyres" of Rosenbusch. *Structure*—Microgranitic and microcrystalline. At times ophitic (many dolerites). *Constituents*—Like diorite.

I. Hornblende fibres may be seen occasionally with the lens, as may the glancing surfaces of ophitic augite in the pyroxene-aphanites or dolerites. These pyroxenic rocks have rod-shaped felspars, and are typically dark-coloured and almost black. Hornblende-aphanites are often grey-green, with a slightly silky lustre.

When altered, as they frequently are, the aphanites are easily scratched with the knife, and are quite distinct from the corresponding types in the more acid groups. "Diabase" is a good field-term for altered greenish rocks allied to diorite, gabbro, aphanite, or dolerite. Hausmann ‡ in 1842 defined it as a rock of any grain containing "hypersthene" (*i.e.*, lustrous augite), labradorite, and chlorite. The term has since been unduly limited.

The ophitic types show a small nodular structure on weathering, due to the thick crystals of pyroxene coming into prominence and preserving the felspars included by them, while the interstitial material is more easily destroyed.

In these altered types, calcite can often be detected with the eye, and fragments of the rock commonly effervesce in acid.

* *Traité de Min.*, 2nde. édit., t. iv., p. 543. Quoted, with "Diorite," by d'Aubuisson in 1819 (*Géognosie*, p. 148).

† *Ibid.*, p. 573.

‡ "Ueber die Bildung des Harzgebirges." Göttingen.

Specific Gravity.—About 2·85 to 2·95.

Typical Analyses.—A. Dolerite without Olivine. "Whin-Sill," Durham. Teall, *Quart. Journ. Geol. Soc.*, vol. xl. (1884), p. 654.

B. Fine-grained "Diabase" (altered and chloritic Dolerite). Near Wieda, Harz. Schilling, *Die Grünstein-genannte Gesteine des Südharzes*, 1869, p. 26.

C. Hornblende-Mica-Aphanite (altered). Gill Bank, near Staveley. Houghton, *Quart. Journ. Geol. Soc.*, 1879, p. 170.

	A.	B.	C.
SiO_2	51·22	46·60	46·17
TiO_2	2·42	...	...
Al_2O_3	14·06	21·60	16·95
Fe_2O_3	4·32	2·86	5·46
FeO	8·73	6·40	0·83
MnO	0·16	...	0·10
CaO	8·33	9·25	10·23
MgO	4·42	6·48	7·13
K_2O	1·25	0·94	3·96
Na_2O	2·55	3·20	2·42
H_2O	1·28	3·10	2·87
CO_2	0·19	0·45	4·84
P_2O_5	0·25	...	...
FeS_2	0·49	...	...
	99·67	100·88	100·96

II. The plagioclases, usually labradorite or bytownite, are rod-shaped, and the hornblendes are commonly also in prismatic forms. The pyroxenes, however, form typically (as in the olivine-dolerites) areas of almost granular crystals occupying the interstices of the felspar mesh, or ophitic crystals enclosing the felspars (compare fig. 39). Magnetite is prominent. The porphyritic crystals are more commonly plagioclase than a ferro-magnesian constituent. Chloritic decomposition-products, epidote, and calcite are common in altered varieties.

Fig. 29.—Altered Dolerite (Diabase). Mynydd-y-Gader, Cader Idris, N. Wales. × 24. *a*, Characteristic pale-brown augite. *e*, Almost colourless epidote, associated with pale chloritic areas, in which it crystallises out, giving elongated sections. *p*, Prismatic plagioclase. *t*, Titanic iron ore.

Varieties of Aphanite.—NEPHELINE-APHANITES and Nepheline-Dolerites occur. The rock of the Löbauer Berg in Saxony, with nepheline, plagioclase, augite, abundant apatite, and magnetite, is a good example.

GRANULAR APHANITE.—Many granular diorites are of sufficiently fine grain to be classed as aphanites.

SUPPLEMENT.

Rocks occur, allied to Diorite and Aphanite, but with a felspathoid in place of the felspar. To these the somewhat loosely employed terms **Nephelinite, Leucitite,** and **Noseanite** have become restricted. One of the best known types is the Nephelinite of Katzenbuckel in the Odenwald, composed of nepheline, a good deal of smaller nosean, augite, some biotite, much apatite, and magnetite. Some "Tinguaites" fall here (p. 225).

Rosenbusch, again, has placed in his "Lamprophyre" group an interesting series of fine-grained rocks, named by him **Camptonite,** and characterised by some 40 per cent. of silica and 5 per cent. of alkalies. In the field, most of these would be collected as aphanites; yet they are clearly an outlying and far more basic group. For a well investigated British series, see Flett, "Trap-dykes of the Orkneys," *Trans. Roy. Soc. Edin.*, vol. xxxix. (1900), p. 874. Many fine-grained "kersantites" and "mica-traps" must be referred to the same outlying group of ultrabasic rocks without olivine.

V. OLIVINE-GABBRO AND OLIVINE-DOLERITE GROUP.

These are the typical basic holocrystalline rocks.

Olivine-Gabbro.—The gabbros without olivine are treated under diorite; but in chemical composition some diorites overlap into this basic group (see p. 227).

Structure—Granitic; often ophitic. *Constituents*—1, Plagioclase (commonly labradorite; sometimes anorthite); 2, Pyroxene, rarely Amphibole or Mica; 3, Olivine. Magnetite or Titanic iron ore is always present.

I. The difference between gabbro and olivine-gabbro is not always clear in hand-specimens, since the olivine decomposes readily to dark patches, in which magnetite is largely developed. The typical pyroxene is brown-black augite, or the schillerised form, diallage. Rhombic pyroxenes are determined microscopically. The felspar is usually grey to blue-grey, and is often saussuritised, losing its vitreous lustre altogether. Mica is rarely seen; but hornblende may replace by paramorphism much of the original pyroxene. The olivine, when fresh, appears in hard yellow-green glassy grains, contrasted with the darker and less transparent pyroxene. If the latter is diopside, it may be difficult to distinguish it from the olivine; its more marked cleavage-surfaces should be noted.

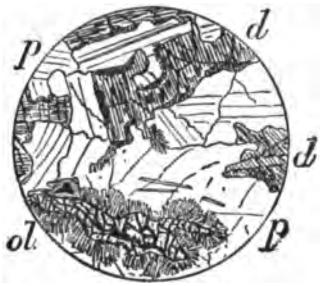

Fig. 30.—Olivine-Gabbro. Near Huntly, Aberdeen. × 7. *d*, Diallage, with numerous inclusions developed by schillerisation. On its margins it is passing by further change into brown strongly pleochroic hornblende, as indicated by the darker bands. *ol*, Olivine with fibrous marginal zone at contact with the felspars (development of actinolitic and other amphiboles; "dynamo-metamorphic" zone of Rosenbusch). *p*, Large crystals of plagioclase.

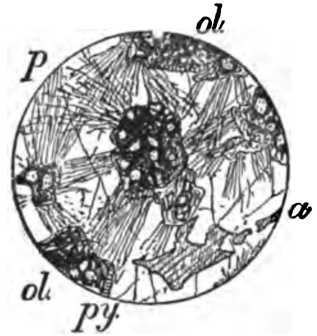

Fig. 31.—Gabbro rich in Olivine (Troctolite). Coverack, Cornwall. × 12. *a*, Irregular and very subordinate augite. *ol*, Olivine, altered, with development of serpentine and magnetite along the cracks. The surrounding felspars have become full of rifts which radiate from the decomposing olivine. *p*, Plagioclase (anorthite). *py*, Thin zones of pale brown pyroxene occasionally occurring on the margin of the olivine.

Ophitic structure on a coarse scale is probably as common as the granitic. Weathering gives a brown rough surface, on which the pyroxene stands out.

Specific Gravity.—About 2·9 to 3·0. As low as 2·8 when much altered.

Typical Analyses.—**A.** Olivine-Gabbro. Cuillin Hills, Skye. Pollard, in Harker, "Igneous Rocks of Skye," *Geol. Surv. United Kingdom*, 1904, p. 103.

B. Anorthite-Gabbro, very rich in olivine, with bronzite and diallage. The Abtthal, Transylvania. Tschermak, *Porphyrgesteine Österreichs*, 1869, p. 227. Anal. by Barber. Placed with "Picrite" by Tschermak (*Ibid.*, p. 280). See p. 236 of this book.

	A.	B.
SiO_2	46·39	42·77
Al_2O_3	26·34	7·48
Fe_2O_3	2·02	3·34
FeO	3·15	4·79
CaO	15·29	6·50
MgO	4·82	30·11
K_2O	0·20	0·10
Na_2O	1·63	0·50
H_2O and loss on ignition	0·58	3·28
TiO_2	0·26	...
MnO	0·14	...
	100·82	98·87

II. The remarks made on the pyroxene-diorites apply equally to these rocks; but olivine must here be especially looked for. It will appear as grains of irregular form, occasionally embedded ophitically in pyroxene, and traversed by the characteristic cracks with traces of green decomposition-products. As alteration advances, the olivine area is converted into green serpentine, and it often becomes a question whether this material has arisen from olivine or from rhombic pyroxene. When the olivine is fairly ferriferous, the portion of ferrous oxide rejected during the conversion into serpentine separates out along the cracks as magnetite, and gives a characteristic appearance to the area. Very commonly, colourless patches of olivine remain in the serpentine, extinguishing together between crossed nicols and thus showing the extent of the original crystal (fig. 31, and frontispiece, fig. 1; also p. xiii.)

When felspar surrounds the olivine, it is often split by the expansion of the latter mineral during hydration, the radial cracks set up being filled with serpentine.

Varieties of Olivine-Gabbro.—WITH SECONDARY ZONES (fig. 30). These are very marked around the olivines. The structure appears to arise by interaction of the minerals when subjected to earth-pressures (as in the "Flaser-gabbros" of Saxony). The constituents become divided from one another by zones of actinolite, rhombic pyroxene or rhombic amphibole, garnet, and other minerals; these zones require the microscope for their correct appreciation.

GABBRO RICH IN OLIVINE (fig. 31).—The "Forellenstein" of the Germans is a rock in which the dark altering olivine, set in white felspar, was supposed to resemble the markings on a trout. Little pyroxene occurs. The felspar is anorthite, and this anorthite-gabbro (with much olivine) was called "Troctolite"* by von Lasaulx. Microscopically, the felspars appear split by the expansion of the olivine during its passage into serpentine. Some authors, noting the small part played by the pyroxene, consider "troctolite" as composed of olivine and felspar only. In chemical composition it is ultrabasic.

Olivine-Dolerite.—*Structure*—Micrograniitic and microcrystalline. At times ophitic. The olivine is often porphyritic. *Constituents*—Like olivine-gabbro.

I. The rock is typically dark, with a granular appearance. Closer inspection generally reveals prismatic felspar, obscured in the total effect by the glancing points of the pyroxene and olivine. Ophitic structure and, where felspar is not abundant,

* *Elemente der Petrographie*, p. 315. From τρώκτη, a trout.

the "lustre-mottling" effect of olivine and pyroxene, are visible in parts of many masses. (See p. 236.)

The knife usually leaves a white mark on the rock, owing to the tendency of the basic constituents to decompose. The joint-surfaces are brown with iron-rust, and weathering gives a rugged aspect like that of the gabbros.

When much weathered, the olivine-dolerites become soft and greenish, and zeolites, calcite, and agates begin to accumulate in cracks and cavities.

Specific Gravity.—About 2·9. Lowered by alteration.

Typical Analyses.—A. Meissner, Hesse. Moesta, 1867; quoted by Roth, *Beiträge zur Petrog.*, 1869, p. cxxx. (one of Haüy's typical Dolerites).
B. Near Valmont, Colorado. Eakins, quoted by Clarke, *Bull. U.S. Geol. Surv.*, No. 168 (1900), p. 140.

	A.	B.
SiO_2	54·39	48·25
Al_2O_3	10·09	16·73
Fe_2O_3	7·07	3·99
FeO	5·79	6·28
CaO	8·89	8·32
MgO	6·49	5·77
K_2O	2·17	4·08
Na_2O	4·16	3·24
H_2O	0·57	1·72
TiO_2	...	·89
P_2O_5	...	·68
Other constituents,	...	·21
	99·62	100·16

II. The plagioclases, labradorite to anorthite, are rod-shaped. The pyroxene occurs in the interstices of the felspar mesh in granular forms, with commonly some sign of the eight-sided outline, or as ophitic crystals. The olivine lies scattered haphazard, two or three crystalline grains commonly being attached together. Porphyritic crystals of plagioclase and pyroxene are frequent. The olivine, moreover, is also commonly porphyritic, not being diffused in small granules through the groundmass.

By alteration, these rocks give rise to dubious forms that are most conveniently styled "Olivine-Diabases," and sometimes become "epidiorites." In these secondary hornblende and biotite may occur. Both these minerals are rare in the unaltered olivine-dolerites.

Varieties of Olivine-Dolerite.—NEPHELINE-OLIVINE-DOLERITE. The felspar may be largely replaced by nepheline, the crystals of which appear as pale yellowish vitreous grains or rectangular and hexagonal sections on the surface amid the dark pyroxene. These rocks are naturally richer in soda than the ordinary

type, and are holocrystalline representatives of the nepheline-basalts.

Supplement.

When felspar is absent, and its place is taken by a felspathoid, we have **Olivine-Nephelinite, Olivine-Leucitite**, &c., a small group of rocks that does not require separate description.

VI. Peridotite Group.

The Peridotites, as the term is now understood, are quite exceptional when compared with the rocks of the preceding groups, being practically devoid of felspar and not rich in any aluminous mineral. They occur as segregated masses, or as veins, among ordinary basic rocks, the latter often shading into them just as granite may shade into the more highly silicated aplite. The "Picrites" of Tschermak* are rocks rich in olivine, this mineral forming about 50 per cent. of the bulk; but some contain much felspar, and they form links with olivine-gabbro. The term cannot fairly be used in any but the general sense of its author. See analysis, p. 233.

Peridotite.—A name used by Cordier for a basalt or dolerite rich in olivine. Now generally adopted, following Rosenbusch, for types without felspar. "Picrite" of many authors. *Structure*—Granitic; but very often the olivine is ophitically included in the pyroxene, amphibole, or mica, giving the "lustre-mottling" effect. *Constituents*—1, Pyroxene, Amphibole, or Mica; 2, Olivine. Magnetite, titanic iron ore, chromite, and other spinelloids are common.

I. The prevalent colour when fresh is a yellow olivine green, darkening with decomposition, and intermingled with black or lustrous bisilicates. In the "lustre-mottling" types, the latter minerals give the impression of forming by far the greater bulk of the rock, owing to the glancing of their cleavage-surfaces or schiller-planes; the olivine appears set in the pyroxene, &c., as little dark green or black granules. A false appearance of coarse crystalline forms is sometimes given to the rock by the meeting at various angles of these lustrous surfaces belonging to different ophitic crystals.

* *Sitzungsber. d. Wiener Akademie*, Bd. xl., p. 113; and *Die Porphyrgesteine Österreichs*, 1869, p. 244.

The hornblende-mica-peridotite of Schriesheim in Baden is a good type of this structure. A beautiful example with bronze-coloured mica occurs near Loch Scye in Caithness ("Scyelite").

Owing to the ready decomposition of olivine, the peridotites are best known in their altered forms, which constitute the great bulk of the rocks called Serpentine.* These are yellow-green, dark green, purple, or red masses, full of veins, which are often of a different colour to the ground; they commonly contain gleaming crystals of altered pyroxene (bastite, &c.), though these are sometimes represented by dull yellowish pseudomorphs in which the cleavage-structures are preserved. The richness of the colour, often a fine purple-black, makes serpentine a striking rock in the field. Owing to its yielding character, schistose and brecciated forms are very common, and the rock breaks along soapy-looking slickensided surfaces. Some rocks called serpentine are serpentinous limestones, others schists with green decomposition-products; and any examination of a serpentine *in situ* should involve a close enquiry into its probable mode of origin.

Traces of dull white saussuritic felspar remain in some serpentines, the original rock having been allied to the gabbros rich in olivine. In others, red or green garnets form a somewhat striking accessory (serpentine of Zöblitz, &c.).

Specific Gravity.—3·0 to about 3·3. Somewhat lower in serpentine, but varying according to the amount of alteration of the constituents.

Typical Analyses.—A. Pyroxene-Peridotite ("Lherzolite"). Caussou Pyrenees. Brunet, quoted by Washington, *Chem. Anal. Igneous Rocks*, Profess. paper 14, U. S. Survey, 1903, p. 357.

B. Mica-Hornblende-Peridotite ("Scyelite"). Loch Scye, Caithness. Mill, *Quart. Journ. Geol. Soc.*, 1885, p. 402. Described by Prof. Judd.

C. Dunite, Dun Mountain, New Zealand. Von Hochstetter, *Zeitschr d. deutsch. geol. Gesell.* 1864, p. 341. Some pyroxene; *chromite removed.*

D. Serpentine, Lizard, Cornwall. J. A. Phillips, *Phil. Mag.*, vol. xli. (1871), p. 101.

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* These are the "ophites" of antiquity; now that "serpentine" is used for a mineral, they are properly "serpentine-rocks."

	A.	B.	C.	D.
SiO_2 . . .	41·50	42·10	42·80	38·86
Al_2O_3 . .	6·93	3·28	...	2·95
Cr_2O_3 . .	trace	...	...	0·08
Fe_2O_3 . .	2·19	8·27	...	1·86
FeO . . .	6·69	2·13	9·40	5·04
MnO . .	trace	0·70	...	...
NiO . . .	...	...	trace	0·28
CaO . . .	5·80	3·77	...	trace
MgO . .	35·90	30·65	47·38	34·61
Alkalies . .	1·67	1·90	trace	1·10
Loss on ignition or H_2O . .	0·32	7·73	0·57	15·52
	101·00	100·53	100·15	100·30

II. The abundance of olivine, unaltered or serpentinised, characterises the peridotites and serpentines in microscopic sections. Felspar is rare, but sometimes surrounds olivine granules here and there, as in the "troctolites." The ferro-magnesian constituents ophitically surround the olivine, or are irregularly mingled with it. Brown-green chrome-spinels, such as picotite, which are isotropic, are occasionally present.

When the peridotite is fresh, there may be very little colour in the section, since the olivine, the enstatite, the diopside rich in chromium, &c., may all appear very clear and pale. The high refractive index of all the typical constituents is a rather striking feature when one passes to these rocks from ordinary quartzose and felspathic types.

The cracks of the olivine will, however, commonly appear faintly green; the pyroxenes can be picked out by their cleavages and extinctions; the spinelloids by their deep colours or opacity, and their isotropism when transparent.

The amphibole that sometimes occupies the place of the more common pyroxene is often also pale and almost colourless in section. A pale brown mica, with strong pleochroism, is an occasional constituent.

The serpentines often contain traces of pyroxene or amphibole amid the general green areas of altered olivine. While these minerals have often become also green, and saturated, as it were, with serpentinous matter, it is questionable whether they contribute in a conspicuous degree to the formation of the mineral serpentine. Their remains, indeed, occur, both in the rock-mass and in sections, rather as breaks in the continuity of the typical soft serpentine-rock than as sources of origin of the

serpentine. (See in particular Miss C. A. Raisin, on the Rauenthal Serpentine, *Quart. Journ. Geol. Soc.*, vol. liii., 1897, p. 246.)

The garnets of some serpentines are greatly altered, zones or complete pseudomorphs of fibrous structure being produced. Calcite and dolomite may occur.

The schistose serpentines should be studied in connexion with sections of the metamorphic rocks among which they occur. Their eruptive origin will probably be proved in a larger number of cases than is at present recognised.

The brecciated serpentines often resemble tuffs under the microscope, since lumps of the rock may lie amid completely pulverised and ground-up material; but there is no scoriaceous structure in the particles, and field-examination will give evidence of the mode of formation of these fragmental varieties.

The fact that serpentinous limestones, chloritic aggregates derived from altered pyroxene-rocks, and other soft green masses, are sometimes described as serpentine must not be forgotten in judging of sections said to represent this rock.

Varieties of Peridotite.—LHERZOLITE would scarcely need to be mentioned separately here, but for the detailed study it has received and the antiquity of the name (given by Delamétherie after the Lake of L'herz in the Ariège). It is a fairly fresh granitic peridotite with diopside, enstatite, and chrome-spinel. Many varieties of peridotite based on the prevailing pyroxene have lately received distinct names; but a mineralogical terminology for such rocks, as above used, will probably commend itself to most observers.

DUNITE (von Hochstetter), or OLIVINE-ROCK, is an extreme form of peridotite, commonly shading into more normal types. It consists of olivine with more or less prominent spinelloids (chromite at the Dun Mountain, New Zealand). The colour is olivine-green, the structure granitic. Many pure serpentines doubtless arise from the alteration of olivine-rock or dunite. A good example of olivine-rock occurs at Kraubat in Styria; and certain yellowish masses with chromite in the Shetlands are serpentines corresponding to the New Zealand dunite. See analysis C.

Note.—**Compact Peridotites**, corresponding to eurite, &c., are rare. The rock of Kraubat, mentioned above, is typically a compact form.

B. Lithoidal Rocks containing some Glassy Matter.

This division includes those types of igneous rock that are not truly holocrystalline, although they may sometimes appear so to the eye. While they commonly occur as lava-flows, they may be found also as dykes, and towards the edges of even more important intrusive masses. There still remain rocks of a highly vitreous character, which are reserved for a separate division C, since their correct determination is more dependent on chemical analyses than is the case in the present or preceding division.

I. Rhyolite Group.

These rocks correspond to the granites and eurites.

Rhyolite (von Richthofen, 1860;* "Liparite" of Roth, 1861.† Prior to these dates classed as trachyte with free silica, and thus often known under the name of "Quartz-Trachyte"). *Structure*— Compact lithoidal, sometimes showing spherulites. Occasional bands or patches of black glass. Often banded and fluidal. *Constituents* — Those of granite may appear porphyritically. The felspar is orthoclase, often in the sanidine condition. Quartz may be present in grains. Ferro-magnesian minerals not conspicuous. Lithoidal to glassy groundmass.

I. The porphyritic crystals in these partly glassy lithoidal rocks are of use in determination according to their abundance. When scattered at wide intervals, their effect on the total composition, the latter being the chief consideration, may be very small. Crystals of orthoclase, coupled with quartz, are, however, a fair guide, since the indeterminable groundmass will probably be yet richer in silica than the aggregate of the porphyritic constituents. The clear "glassy" sanidine or anorthoclase will often show the characteristic simple twinning as the specimen catches the light when turned in the hand; the quartz is commonly granular, but sometimes has traces of pyramidal form. Little black specks frequently occur, which prove to be flakes of biotite or prisms of soda-augite, or, more rarely, hornblende.

The groundmass is typically pale in colour, often being a red or brown-pink, or a yellow-brown; sometimes white

* *Jahrbuch der k. k. Geol. Reichsanstalt*, Bd. xi., pp. 156 and 165.

† *Die Gesteinsanalysen*, p. xxxiv.

or greenish-white. The banded structure is often extremely perfect, as in rhyolites from Iceland, the rock splitting along parallel planes almost like a shale. In less regular types the bands, marked out by various shades of colour, are bent or contorted by the flow, and the porphyritic crystals play a part in distorting them which is comparable to that of the "eyes" in schists.

The groundmass, when compact, is fairly hard (= nearly 6 when fresh), and the fractured surfaces tend to be conchoidal. It gives a good potassium reaction in the flame. When attacked by volcanic vapours or atmospheric action, it becomes powdery and softer; opals are found sometimes in the cavities.

A scoriaceous and commonly pink type from Hungary goes by the name of the "Millstone-Porphyry."

The groundmass may become very glassy, approaching obsidian when still compact, or becoming white and pumiceous, with a delicate silky lustre and rough feel, when expanded by abundant steam-vesicles.

As already hinted, spherulitic structure may be recognised, particularly in the lithoidal bands. The spherulites are sometimes greatly elongated by the flow of the mass in which they are developed. Lithophyse-structure and spherulites, the centres of which seem to have been eaten out by decomposing agents, may be looked for among rhyolitic lavas. In some cases, the spherulites seem to have grown, both outwards and inwards, from the surfaces of steam-vesicles.

The freshest series of rhyolites in the British Isles, ranging from lithoidal types to perlitic obsidian, is undoubtedly to be found on Sandy Braes, north of Tardree in Co. Antrim.

The older types of rhyolite have special interest in Great Britain, owing to their extensive development in Ordovician and earlier times. Secondary devitrification has removed all traces of glass, but the structures exactly parallel those occurring at the present day. Their general appearance is that of compact white or grey eurite; but spherulites and lithophyses can often be well seen upon the joint-planes or other surfaces affected by weathering. In the hollows of the altered spherulites, and in the cracks of the rock, quartz is very freely developed. Many of these dull or flinty-looking lavas represent former obsidians.

The "Pyromerides" (*Haüy* and *Monteiro*,* meaning "only in

* *Journal des Mines*, tome xxxv. (1814), p. 359.

part fusible") of the Continent are precisely similar to the old British coarsely spherulitic rhyolites. Secondary quartz and chalcedony are abundant in them. The spherulites, as in our Wrekin area, have often become red, almost like jasper, but still show radial structure when broken open. In the Wrekin area the surrounding devitrified glass is dark green; in the typical "pyromeride" from Wuenheim in the Vosges it is yellowish white, resembling many "elvans."

Where the glass was formerly abundant in these ancient rhyolites, perlitic cracks of the most perfect kind may often be traced with the eye and lens on slightly weathered surfaces; these cracks may be marked out by secondary products darker than the devitrified groundmass. It is on their occurrence that geologists mainly rely for proof of the former vitreous character of the mass.

These older rhyolites include very many of the "quartz-porphyries" of continental writers, and part of "felsite," "felstone," "petrosilex," and "halleflinta."

Specific Gravity.—About 2·5. By secondary devitrification this rises to 2·65.

Typical Analyses.—A. Rhyolite, Hlinik, Hungary. Von Sommaruga, *Jahrbuch d. k. k. geol. Reichs.*, Vienna, 1866, p. 464. "Like hornstone."

B. Lithoidal Rhyolite, Tardree, Co. Antrim. Player, quoted by Teall, *Brit. Petrogr.*, p. 348. With tridymite.

C. Perlitic Rhyolite altered by secondary devitrification. Early Cambrian or Pre-cambrian age. W. of the Wrekin, Shropshire. J. A. Phillips, *Quart. Journ. Geol. Soc.*, 1877, p. 457. Described by Mr. S. Allport.

	A	B	C
SiO_2	74·17	76·4	72·18
Al_2O_3	13·24	14·2	14·46
Fe_2O_3	...	1·6	1·78
FeO	3·24	...	0·91
MnO	...	...	trace
CaO	1·46	0·6	0·92
MgO	0·32	...	trace
K_2O	5·38	4·2	6·10
Na_2O	1·87	1·8	1·92
H_2O and loss on ignition	1·05	1·5	1·47
	100·73	100·3	99·74

The percentage of silica often rises considerably in the older

examples, bases being carried away in solution and quartz and chalcedony greatly accumulated. Thus a coarsely spherulitic rhyolite at Digoed, N. Wales, gives $Si\,O_2$ = 83·08 per cent.

II. In sections of rhyolite the porphyritic crystals are corroded and eaten into by the groundmass (fig. 32, B), assuming commonly a rounded or oval outline. The quartz, which occurs frequently, may show glass-enclosures with bubbles, which are not due, like many "enclosures," merely to the transverse section of a tongue of the invading groundmass.

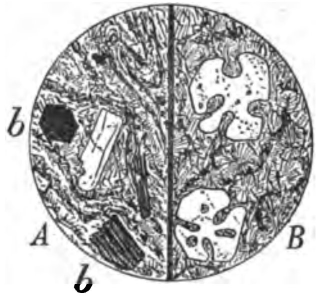

Fig. 32.—A, Rhyolite. Hlinik, Hungary. × 24. Fluidal, banded, and imperfectly spherulitic structures. *b*, Basal and vertical sections of brown biotite. A crystal of sanidine occurs. B, Rhyolite. Dyke, Broadford Bay, Skye. × 24. Spherulitic groundmass, with porphyritic quartz crystals which have been much corroded by the surrounding matter.

Soda-augite and biotite are the most common ferro-magnesian constituents, and keep their outlines well; but the dark minerals, including magnetite, are often only feebly represented.

The groundmass shows bands of various brownish tints, commonly yellow-brown (fig. 32, A), or is uniformly brown with scattered embryo-crystals—"crystallites" or "microlites." These small crystalline bodies are arranged with their longer axes parallel to the lines of flow, and should be studied with a $\frac{1}{4}$-inch or $\frac{1}{8}$-inch power. The embryo-felspars are often notched deeply at each end, having grown, in fact, most rapidly from their corners (compare fig. 36, B).

Spherulites appear as brown circular sections, sometimes with a porphyritic crystal at the centre. The radial fibrous structure may or may not be developed (see fig. 41), and concentric coats of slightly different physical constitution appear in some varieties. The material, partly glassy, partly crystalline, forming the spherulite differs but little in composition from the general groundmass. In some cases, a differentiation occurs among the rays composing the spherulite, and some of the browner rays even exhibit pleochroism. Probably in all spherulites there is a good deal of glass, caught up during the process of aggregation. A more transparent coat commonly surrounds the completed spherulite; at other times a cloud of dusky matter remains, from which the spherulite has concreted.

In more exceptional cases the spherulite has grown in some directions more than in others, spreading out in rays into the

surrounding glass in a striking amœbiform manner. Such bodies may be described as "skeleton-spherulites;" a bunch of the divergent rays when cut across gives a number of irregularly ovoid sections of fibrous matter with no apparent connexion between them.

In the more lithoidal rhyolites, the spherulitic structure, if present, is injured by the close crowding of the spherulites (fig. 32, A and B) and is best seen between crossed nicols. Apart from the minute traces of isotropic glass, a shadowy crystalline effect (due to glass under stress, imperfectly developed crystals, and microlites) is seen throughout the groundmass when polarised light is used. This "cryptocrystalline" character is probably better seen in the rhyolites than in any other group.

The spherulites, when numerous, may have polygonal outlines where they come into contact, or may be reduced to fan-like patches. With crossed nicols the black cross of spherules under stress or of fibrous aggregates is generally traceable, and is very conspicuous in some small spherulites in glassy rocks. In the imperfect fan-like aggregates, this feature becomes most easily noticeable when the stage is rotated.

While common brown spherulites may be almost or truly isotropic, the colourless coat round well developed examples is seen to be better crystallised than the interior.

Perlitic structure, with its more or less delicate and complex system of rifts, appears in the most glassy rhyolites, the curved cracks at times resembling in regularity the coats of an onion (see fig. 42). The structure is little interfered with by spherulites, the cracks often passing through them and the groundmass alike; and the whole glass may be brown with separated matter and full of microlites, and yet may have yielded to this form of contraction. But the sub-crystalline structure of the most lithoidal rhyolites checks the formation of perlitic structure.

The older rhyolites show under the microscope all the structures above described. But for a certain earthy dulness of the groundmass, and the frequent occurrence of cracks and hollows filled with chalcedony, quartz, or darker secondary products, their extremely antique character might scarcely be suspected (see fig. 42). But, directly the polariscope is applied, the areas representing the glassy or glassy-lithoidal matrix are seen to be composed of crystalline granules, giving colours of a low order; while any spherulites present, though all their form and fibrous structure may be preserved, also exhibit a granular polarisation. The microlites and minute bodies of the groundmass can be traced, often as pseudomorphs, with higher powers, despite the secondary devitrification that has gone on round

them. The granules developed by this process sometimes attain 1 mm. or so in diameter, and they meet one another along irregular boundaries. The structure is thus something like that of quartzite, and it is quite possible that each granule, felspathic or otherwise, is formed in optical continuity with some minute original central crystal which has served as a *point d'appui* during the process of devitrification. Thus a rock that retains all the delicate structures of the original glassy type, may come to consist of a holocrystalline aggregate of interlocking crystals of quartz and felspar, which behave ophitically towards the crystallites and microlites originally developed. Twinning, however, does not seem to arise in these secondary felspathic grains.

Varieties of Rhyolite.—SODA-RHYOLITE. This corresponds to soda eurite. The orthoclase is rich in soda, and commonly albite or oligoclase appears. Soda-microcline is probably present. These rocks are called "Quartz-Pantellerites" by Rosenbusch, and form links with the quartz-andesites. See also Obsidian in division C.

II. TRACHYTE GROUP.

This group is now by universal consent much reduced in bulk, by the cutting off of the quartz-trachytes (rhyolites) at one end, and the oligoclase-trachytes, &c. (andesites), at the other. It thus corresponds to the syenites.

Trachyte (*Haüy*,* quoted by d'Aubuisson, 1819, from τραχύς, "rough," owing to the common texture of such lavas). *Structure* —Compact lithoidal; very often scoriaceous. Commonly porphyritic. *Constituents*—Those of syenite. The orthoclase is commonly the "glassy" sanidine. Ferro-magnesian constituents not abundant. Lithoidal to glassy groundmass.

I. Quartz must be absent; the sanidine is often large, its clinopinacoids being characteristically broad and the crystals plate-like. Soda-augite, biotite, and hornblende may be recognised, and occasionally rhombic pyroxene occurs. Plagioclase is common, and may be known by its striated surfaces.

As in the rhyolites, the groundmass is typically pale. The characteristic colour is white, inclining to grey-brown; but reddish, yellowish, and even black trachytes exist. The black scoriaceous type seen in the Arso lava-stream in Ischia, which was poured out in the fourteenth century, is, however, quite exceptional.

Since the proportion of glass to well-developed crystals is on the average less in the trachytes than in the rhyolites, the banded and spherulitic structures are less often seen. The fractured surface is somewhat rough, and the material breaks away under the knife. In decomposing trachytes, alum is sometimes deposited under the influence of solfataric vapours.

* *Traité de Min.*, 2nde. édit., t. iv., p. 579.

Specific Gravity.—About 2·5. The looseness of texture in many examples makes determination difficult.

Typical Analyses.—A. Rabertshausen, Hesse. Engelbach, quoted by Zirkel, *Petrographie*, ed. 1, Bd. ii., p. 178. Little hornblende and mica.

B. Freienhäuschen, Eifel. Zirkel, *Zeitschr. d. deutsch. geol. Gesell.*, 1859, p. 535. With *Oligoclase.*

C. Scarrupata, Ischia. Vom Rath, *Zeitschr. d. deutsch. geol. Gesell.*, 1866, p. 623. With *Sodalite*, Augite, and Biotite.

	A.	B.	C.
SiO_2	62·39	60·01	65·75
Al_2O_3	20·23	21·03	17·87
FeO	5·32	8·48	4·25
CaO	1·09	3·19	1·33
MgO	0·86	0·73	0·52
K_2O	5·76	2·01	3·48
Na_2O	3·90	4·29	5·67
Loss on ignition and H_2O	2·02	...	0·78
Cl	...	...	0·34
	101·57	99·74	99·99

II. The beautifully clear sanidine crystals are usually conspicuous in sections of trachyte, though liable to be broken and corroded. Plagioclase is almost always present. Small soda-augites are probably the commonest ferro-magnesian constituent; biotite is fairly frequent, but hornblende somewhat rarer.

The groundmass rarely shows banding, but is crowded with microlites of orthoclase, which are arranged in confused flowing lines. A high power reveals colourless interstitial glass with "crystal-dust" and minute skeleton-crystals. In the most glassy trachytes, spherulitic and perlitic structures appear (see Rhyolite).

Fig. 33.—Trachyte. Ischia. × 12. *b*, Biotite. *o*, Orthoclase (sanidine) in fresh crystals, showing traces of zoning. Cleavages not distinct. Green soda-augite occurs; a cross-section lies near the top of the drawing. Fluidal hemicrystalline groundmass.

The older trachytes are very difficult to mark off from the corresponding type of rhyolite, since it is impossible to say what was the original proportion of silica present. The marked absence of porphyritic quartz in some rocks at present classed as altered rhyolites makes one suspect that (among the Devonian eruptions, for instance) many of these old lava-flows were trachytic.

Varieties of Trachyte.—SODA-TRACHYTE ("Pantellerite" of Rosenbusch, after Förstner, from Pantelleria). Soda-microcline may be

present, with oligoclase. Probably the majority of trachytes contain a greater total percentage of soda than of potash (see Phonolites below).

TRACHYTE WITH MUCH OLIGOCLASE.—The "Domites" of von Buch (from the Puy de Dome) may be placed here. These rocks are the connecting link with the andesites.

NEPHELINE-TRACHYTE (NEPHELINE-PHONOLITE).—These rocks may be regarded as forms of trachyte rich in soda and poor in silica. The rocks known early in the century as Phonolites * were compact grey fissile lavas which gave a ringing sound ("Clinkstone") when struck with the hammer. Nepheline was gradually discovered in many of these, and, following Zirkel, the term phonolite is now used for a lithoidal or glassy rock containing—1, Orthoclase (usually rich in soda); 2, one of the "felspathoids," *i.e.*, Nepheline, Leucite, Nosean, or Haüyne; 3, Pyroxene, Amphibole, or Mica. Pale sphene is a common accessory.

I. The nepheline-phonolites are less trachytic in aspect than many of their allies. They are commonly very compact, and of a grey colour faintly tinged with brown. When fresh they have a peculiar partly glassy, partly greasy lustre, due to the disseminated nepheline (the rock of Brüx, Bohemia, for example). But alteration easily sets in, and yellowish-white opaque patches, often showing nepheline outlines, appear throughout the mass. The cracks and hollows become filled with zeolites, notably natrolite. The felspar remains distinct and glassy-looking long after the nepheline has become pseudomorphosed.

The fissile character common in phonolites is intensified by weathering. In several cases it is due to the arrangement of lamellar orthoclase in parallel planes during movement of the viscid mass.

As was noticed nearly a century ago, the phonolites give on digestion in acid a separation of gelatinous silica. Any rock rich in zeolites is likely to show this character; but the nepheline and its alteration-products, dissiminated through the whole mass, make the reaction here a striking one. It is noteworthy that the more weathered phonolites give only slight gelatinisation, since the minerals which thus easily yield their silica have been already attacked by circulating waters (see Zirkel, *Petrographie*, 1866, Bd. ii., p. 196).

Specific Gravity.—Near 2·55.

Typical Analyses.—A. Nepheline-Phonolite. Marienberg, near Aussig, Bohemia. Rammelsberg, quoted by Roth, *Beiträge zur Petrogr.*, 1873, p. xxxviii.

* Klaproth, *Abhandl. der Berlin Akad.*, 1801.

B. Nosean-Nepheline-Phonolite. Wolf Rock, Cornwall. J. A. Phillips, *Geol. Mag.*, 1871, p. 249. Described by Mr. S. Allport. See also *Geol. Mag.*, 1874, p. 462.

C. Nepheline-Nosean-Sodalite-Phonolite. Black Hills, Dakota. *Bull. U.S. Geol. Surv.*, No. 148, p. 114.

	A.	B.	C.
SiO_2	53·84	56·46	57·86
Al_2O_3	19·68	22·29	20·26
Fe_2O_3	4·83	2·70	2·35
FeO	...	·97	·39
MnO	...	trace	·21
CaO	3·16	1·47	·89
MgO	1·93	trace	·04
K_2O	7·98	2·81	5·19
Na_2O	6·02	11·13	9 47
H_2O and loss on ignition,	3·76	2·05	2·61
P_2O_5	...	trace	·03
Other constituents, . .	...	...	·67
	101·20	99·88	99·97

II. The nepheline, though often abundant and porphyritic, is very seldom clear and fresh. The form of its sections, even in the earthy-brown decomposed state, makes it readily recognisable. The hexagonal sections, which are isotropic, must not be alone considered, since they may easily resemble, in their altered state, the common sections of nosean.

The felspars and the groundmass, which contains commonly soda-augite, need no remark (see ordinary Trachyte). The nepheline may, however, occasionally occur as minute rectangular and hexagonal sections in the groundmass itself, and entangled in the felspar mesh. Even in this truly microscopic condition, the regularly grouped enclosures may often be detected in the crystals.

Fig. 34. — Nepheline - Trachyte (Phonolite). Brüx, Bohemia. × 35. *n*, Nepheline, in rectangular and hexagonal sections, showing zoning. *o*, Orthoclase (sanidine), in numerous needles and in stellar groups. Dark green patches (soda-pyroxene) occur in the hemicrystalline groundmass.

Sphene is a common accessory constituent. The presence of nosean or leucite links nepheline-trachyte with the varieties which follow.

LEUCITE - TRACHYTE (LEUCITE-PHONOLITE).—Here the potash predominates largely over soda, but, perhaps from a deficiency of silica, leucite occupies part of the place taken by orthoclase in ordinary trachytes.

I. The leucite is often visible

only with the microscope. The rock has a less compact and more earthy texture than the typical nepheline-trachytes. Nosean, in dull-looking or dark altered crystals, is very often present.

II. The almost circular sections of the clear and scarcely altered leucite, unless very minute, readily strike the eye. They are sometimes distributed almost regularly through a dull groundmass, and at the first glance resemble vesicles. The characteristic enclosures are better seen in the small than in the large porphyritic crystals. Hexagons of nosean, and sometimes nepheline, are frequent accessories.

NOSEAN- or HAÜYNE-TRACHYTE (NOSEAN-PHONOLITE). — The dull sections of the felspathoid, sometimes earthy-brown when nosean, sometimes almost blue-black when hauyne, are commonly visible on the surface of the rock, and are easily detected under the microscope. The nosean-nepheline-trachytes resemble grey compact typical phonolite (as, for example, the only known British phonolite, from the Wolf Rock, Cornwall). See analysis B. The nosean-leucite-phonolites are typically of looser and more earthy texture.

III. ANDESITES RICH IN SILICA (RHYOLITIC ANDESITES).

This group, in which the excess of silica may or may not be developed as quartz, corresponds to the quartz-diorites and quartz-aphanites. But the latter probably form a larger group, owing to their having been developed in many cases as quartzose "epidiorites" from rocks in which the percentage of silica was originally lower. Very many glassy rocks, however, that have been classed with rhyolites have porphyritic crystals of plagioclase; and their chemical composition would lead one to conclude that little, if any, orthoclase would be developed if the whole mass became holocrystalline. Such cases must be worked out in the field and correlated, if possible, with holocrystalline types. As Mr. Diller and Prof. Judd have shown, the proportion of porphyritic crystals to glass is a very important element in these considerations, and a hand-specimen from one part of a rock-mass must be referred to andesite rich in silica, while another, with more crystals, may be a normal or even basic andesite.*

The characters of the rocks of this group are so much the same as those of the andesites which follow that separate description is unnecessary. Quartz grains, often corroded, must be looked for

* Diller, *Science*, vol. iii. (1884), p. 653, and Judd, "Natural History of Lavas," *Geol. Mag.*, 1888, p. 4.

(as in the "Dacites," so named by Stache, after Dacia). There is a greater tendency, moreover, to the formation of glassy types than is the case among normal andesites. The much altered forms with free quartz are often called "Quartz-Porphyrites."

It must be remembered that "Quartz-Andesites" may occur which scarcely fall within this group, the bulk-analysis yielding perhaps only 61 per cent. of silica. Others seem merely to have picked up foreign quartz-grains in their passage to the surface. The quartz in such cases is surrounded by a green envelope of granular pyroxene.

Specific Gravity.—About 2·65.

Typical Analyses.—A. "Dacite." Kis Sebes, Transylvania. Doelter, *Tscherm. Mittheil.* (*Jahrb. d. geol. Reichsanst*), 1873, p. 92. Biotite, Hornblende, Augite. A little Sanidine.

B. Hypersthene-Augite-Andesite; pumiceous form, the glass forming 90 per cent. of the whole bulk. Krakatoa. Winkler, quoted by Judd, *Roy. Soc. Krakatoa report*, part i., p. 32.

	A.	B.
SiO_2	66·32	68·99
TiO_2	...	0·82
Al_2O_3	14·33	16·07
Fe_2O_3	5·53	2·63
FeO	0·25	1·10
MnO	...	0·28
CaO	4·64	3·16
MgO	2·45	1·08
K_2O	1·61	1·83
Na_2O	3·90	4·04
Loss on ignition	1·13	omitted
	100·16	100·00

IV. Andesite Group.

The name Andesite, which was used for certain lavas of the Andes by von Buch, was resuscitated in 1861 by Roth* for rocks between trachyte and basalt, consisting of oligoclase with amphibole or pyroxene.

The group is a very large one, its members being among the commonest lavas met with; and two sub-groups suggest themselves, which of course shade into one another, but which will serve to emphasise the difference of type at opposite ends of the series. See also p. 249.

* *Die Gesteins-analysen*, p. xlv.

The first sub-group, called here "trachytic andesites," corresponds to diorites rich in silica. The second, the "basaltic andesites," corresponds to the pyroxene-diorites with basic felspars, and thus to the bulk of "gabbros without olivine."

Sub-group 1.—Trachytic Andesites. *Structure*—Like trachyte. Commonly porphyritic. *Constituents*—1, Plagioclase (commonly Oligoclase); 2, Soda-Augite, Hornblende, or Mica. Sometimes Rhombic Pyroxene. Lithoidal to glassy groundmass.

I. The marked feature of the andesites is the absence of orthoclase; in this sub-group the striated oligoclases are abundant and the ferro-magnesian constituents are less important. The groundmass is characteristically trachytic; colour on the whole darker than in trachyte. Spherulitic and other structures characteristic of the more glassy rocks are rare.

The much altered and older examples (many of the "Porphyrites") are typically brown-red and almost earthy in appearance. Search should be made in the field for the least altered portions of the mass.

Specific Gravity.—About 2·75.

Typical Analyses.—Poor in magnesia, and fairly rich in alkalies.

A. Hornblende-Andesite. Wolkenburg, Siebengebirge. Bischof, *Lehrb. d. Geol.*, 1 Aufl., Bd. ii., p. 2181.

B. Hornblende-Andesite with Augite. Puy de Louchadière, Auvergne. Von Lasaulx, *Neues Jahrb. für Min.*, 1869, p. 708.

	A.	B.
SiO_2	62·38	60·52
Al_2O_3	16·88	16·51
Fe_2O_3	7·33	...
FeO	...	7·91
CaO	3·49	5·84
MgO	0·82	1·41
K_2O	2·94	2·32
Na_2O	4·42	4·96
Loss on ignition and H_2O	0·87	0·23
	99·13	99·70

II. The broad sections of felspar that characterise this type of andesite are often as fresh and clear as sanidine, but show beautiful twin-lamellation. The glassy groundmass has com-

monly penetrated them and worked far into their interiors, the corrosion spreading easily along the planes of composition of the twins. The extent to which these plagioclases have yielded to the attack of the magma is a feature of great interest; and the external matrix has often become dull by the development of crystallites, while the intruded portions have preserved a purely glassy character.

Fig. 35. — Hornblende-Andesite (trachytic type). Summit of Beinn Nevis, Scotland. × 7. *h*, Brown hornblende. *p*, Plagioclase, often much corroded by the glass around. Fluidal hemicrystalline groundmass.

The hornblendes or micas, again, suffer by the development of an opaque black margin, and sometimes remain as black granular pseudomorphs.

Rich brown biotite is again and again associated in these rocks with hornblende. The typical pyroxene is very pale green and is probably soda-augite; and rhombic forms, generally poor in iron, may appear.

The groundmass is brownish and trachytic in appearance. The glass, where traceable, is pale and almost colourless. Evidences of flow are less frequent than in the trachytes.

The "Porphyrites" (altered andesites) of this sub-group show typically a brown earthy matrix, often with green pseudomorphs after biotite. The hornblende and pyroxene have commonly become completely decomposed, leaving colourless areas bounded and traversed by strong opaque bands, which are formed by the iron oxides separated out along the cracks and on the margins of the original crystals. The glass of the groundmass, and that intruded into the felspars, can sometimes be traced as yellow areas occupied by decomposition-products, which resemble serpentine between crossed nicols.

Sub-group 2.—**Basaltic Andesites.** Typically Pyroxene-Andesites. "Basalt without olivine" comes here, when there is about 50 per cent or more of silica. *Structure*—Lithoidal; sometimes with glassy interspaces between the crystals. *Constituents*—1, Plagioclase (Oligoclase or, probably more often, Labradorite); 2, Augite or Rhombic Pyroxene; more rarely Hornblende and Mica. Magnetite is conspicuous. Lithoidal to glassy groundmass.

I. In appearance these rocks are darker and compacter than

those of the preceding sub-group, and approach the basalts in texture, becoming even black and notably heavy. The rock tends to break conchoidally, and a spheroidal structure in the mass is not uncommon, which is developed, with onion-like effect, by weathering. The porphyritic crystals of plagioclase are often accompanied by well developed pyroxene, the stout black prisms of which stand out on the surface amid the deep brown groundmass.

The mass of the rock appears microcrystalline to the eye and lens, the small rod-shaped felspar prisms being often discernible. It is scratched by the knife, leaving a light streak. When much glass is present, dark areas appear, with a quartz-like aspect and conchoidal fracture, between the crystals, and the whole rock may have a speckled vitreous lustre when turned about in the hand. Spherulites, banding, &c., are rare; and scoriaceous rather than pumiceous structure accompanies the examples gathered from lava-streams.

The much altered types (part of "Porphyrite" and "Diabase") are commonly reddish, like those derived from the trachytic andesites; or compact black, like many of the rocks styled by Brongniart "Melaphyre," * a number of which must come into this sub-group.

Specific Gravity.—About 2·75 to 2·9.

Typical Analyses.—Richer in lime and magnesia and poorer in alkalies than preceding sub-group.

A. Augite-Andesite. Tunguragua, Andes. Artopé, quoted by Roth, *Beiträge zur Petrogr.*, 1873, p. xlvi.†

B. Hypersthene-Augite-Andesite, Buffalo Peaks, Colorado. Hillebrand, *Bull. U.S. Geol. Survey*, No. 1, p. 26.

C. Pyroxene-Andesite. Delta, Shasta Co., California. Melville, *Bull. U.S. Geol. Surv.*, No. 168 (1900), p. 176. A trace of olivine.

	A.	B.	C.
SiO_2	58·35	56·190	55·08
Al_2O_3	16·74	16·117	18·93
Fe_2O_3	...	4·919	2·02
FeO	6·71	4·433	5·56
MnO	0·54	trace	...
CaO	6·81	6·996	8·40
MgO	4·84	4·601	5·17
K_2O	1·18	2·368	0·74
Na_2O	4·69	2·961	4·23
H_2O	0·31	1·028	0·29
P_2O_5	...	0·266	...
		Cl 0·022	TiO_2 trace
	100·17	99·901	100·42

* *Classification minéral. des Roches Mélangées*, 1813, p. 40.

† The glassy augite-andesite of Eskdale, Dumfries, has a closely similar composition. See Teall, *Petrogr.*, p. 196.

Compare description of olivine-basalts, p. 257.

II. In sections the prominence of pyroxene, whether pale or strongly yellow-brown and purple-brown, and the comparative lack of hornblende and mica, strike the eye at once. The latter minerals are, in fact, typically absent.

Augite occurs porphyritically, and has developed abundantly in the groundmass in the more basic types ("basalts without olivine"), occurring there as grain-like crystals between rod-shaped felspars; the rock passes, by exclusion of the interstitial cryptocrystalline matter, into typical "dolerite without olivine." Enstatite or hypersthene is common (fig. 36, *A*).

The plagioclase, when porphyritic, is freely corroded, preserving a general prismatic outline, though the interior may be largely replaced by a maze-like structure of brown glass. As above remarked, a mesh of rod-shaped plagioclases developes in the groundmass in the most basic types.

In some varieties of andesite from near Tetschen in Bohemia

Fig. 36.—*A*, Pyroxene-Andesite (basaltic type). Kremnitz, Hungary. × 14. *p*, Plagioclase. *r.p*, Rhombic pyroxene (enstatite). Crystals of magnetite occur. Dark hemicrystalline groundmass. *B*, Glassy Pyroxene-Andesite (basaltic type). Dyke, Eskdale, Dumfries. × 40. *a*, Granular augite, often set with radiating microlites from the glassy groundmass. *p*, Plagioclase in various stages of growth, often with characteristic bifurcating and incomplete terminations. Magnetite occurs. This rock exhibits the clear brown interstitial glass typical of many continental augite-andesites and "porphyrites."

the felspar is mainly in the cryptocrystalline groundmass, in which abundant microlites of brown hornblende have developed.

The porphyritic crystals are, on the other hand, large augites, with very pronounced idomorphic characters in section. This rock will serve to show how removed the basaltic andesites may be from the trachytic type.

The groundmass is characteristically brown, with at times skeleton-crystals (cross-like forms) of magnetite. When completely glassy, it is a warm transparent brown (fig. 36, *B*), in which the well-defined crystals of the final consolidation lie.

When the groundmass appears filling the interstices of the felspar mesh, it is described by Rosenbusch as "intersertal." Were it now to become converted into large crystals, it would often result in an ophitic structure, since its composition must often be near that of a pyroxene, the felspathic matter having been withdrawn from it. In the same rock-section the structure of a basaltic andesite with a felspar mesh may be seen in one part, and that of ophitic dolerite in another (compare fig. 39).

The "Porphyrites" of this sub-group show a yellowish substance in the place of any original glass. The rhombic pyroxenes are decomposed to green fibrous forms; the augites are often replaced by chlorite, and the felspars in large part by calcite. Specks of calcite may also appear throughout the groundmass.

Varieties of Andesite.—Beyond the above broad divisions of the andesites, we may expect the following varieties:—

NEPHELINE-ANDESITE (NEPHELINE-TEPHRITE).—The "Tephrites" are a plagioclase-series parallel to the phonolites, and commonly containing soda-augite. The name is unfortunate, since the old "Téphrines" are rarely "tephrites" in the restricted sense of Rosenbusch, being mostly rough grey andesites. "Basanite" of Rosenbusch is a tephrite with olivine; such rocks will be classed here as varieties of olivine-basalt. The "basanite" of Brongniart (1827) was merely a porphyritic basalt. A "tephrite" is practically an andesite with part of the felspar replaced by a felspathoid (p. 247). The nepheline-andesites seem rarer than the nepheline-trachytes. The silica sinks to about 50 per cent.

LEUCITE-ANDESITE (LEUCITE-TEPHRITE). — The leucites are often conspicuous on the surface of the rock, as in the fine example from Cività Castellana near Viterbo.

NOSEAN- or HAÜYNE-ANDESITE (NOSEAN-TEPHRITE).—Haüyne is more prevalent than nosean, doubtless owing to the presence of lime rather than soda in the molten rock. A very fine example is the so-called "Haüynophyre" of Melfi; some parts of this rock, with only 43 per cent. of silica, cannot fairly be ranged as andesite.

Note to the Andesites.—PROPYLITE, used by von Richthofen for the oldest Tertiary andesites, has been revived by Rosenbusch for those forms in

which alteration has been due to solfataric action. The typical propylites in this sense are compact grey rocks in which the hornblende and biotite are converted into green chloritic pseudomorphs, while the felspars have often given rise to epidote. Iron-pyrites is in some cases abundantly developed in minute sparkling crystals throughout the rock. To accurately distinguish between this kind of alteration and that of the ordinary "porphyrites" requires careful study on type-examples. For preliminary purposes neither name need be used, "altered andesite" being sufficient and comprehensive. The Propylites have been fully discussed by Prof. Judd (*Quart. Journ. Geol. Soc.*, vol. xlvi., 1890, p. 341).

SUPPLEMENT.

A somewhat interesting group of rocks falls here, the **hemicrystalline Nephelinites, Leucitites**, &c., which are much better known than their holocrystalline representatives. As Prof. Lawson has suggested (see p. 223), orthoclase may, in the latter, sometimes represent the leucite of the lava-type; and, similarly, other felspars may represent the other felspathoids. *Structure*—Commonly porphyritic, with a trachytic aspect. *Constituents*—1, Nepheline, Nosean, Haüyne, or Leucite; 2, Pyroxene, Amphibole or Mica. Lithoidal to glassy groundmass.

I. The absence of felspar may not persist throughout the same rock mass, and a Nephelinite may thus graduate into a Nepheline-andesite.

A well-known example is the Leucitite of Selberg, near Rieden in the Eifel (fig. 37), with leucite, nosean, minute haüyne, and soda-augite.

Its mean analysis is as follows :—Nosean-Leucitite. Rieden. Vom Rath, *Zeitschr. d. d. geol. Gesell.*, 1864, p. 97.

SiO_2	48·25
Al_2O_3	16·63
FeO	6·53
CaO	7·82
MgO	1·23
K_2O	6·52
Na_2O	9·42
SO_3	1·68
CO_2	1·10
Cl	0·26
H_2O	1·94
	101·38

In proportion of silica these rocks resemble the basic and ultrabasic series, while in alkalies they may surpass the phonolites.

II. The pyroxene is a green soda-augite, often markedly pleochroic, or a brown augite, as in the haüyne-augite rock of

Neudorf; the former type is common in rocks of a trachytic character, and the latter in those of distinctly basaltic aspect.

V. Olivine-Basalt Group.

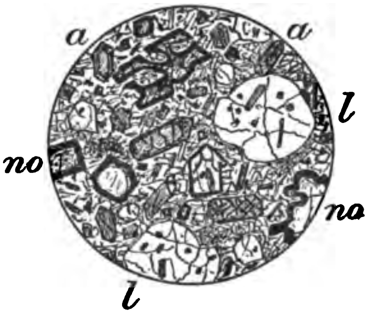

Fig. 37.—Nosean-Leucitite. Rieden, Eifel. × 7. *a*, Dark green pleochroic soda-augite, often zoned. *l*, Leucite, including small soda-augites and microscopic haüynes. *no*, Nosean, with darkened and corroded borders. Hemicrystalline groundmass.

If we remove the few rocks of basaltic type in which olivine is not present to the sub-group of the basaltic andesites, the present group might bear simply the old name "Basalt." To avoid any misconception, however, we add, as in the case of the holocrystalline representatives, the prefix "olivine."

Olivine-Basalt.—*Structure*—Lithoidal; in parts ophitic. *Constituents*—1, Plagioclase (commonly Labradorite or Anorthite). 2, Augite; Rhombic Pyroxene at times, but less frequent than in the basaltic andesites, its place being taken by olivine; Mica or Amphibole is rare, particularly the latter. 3, Olivine. Magnetite and titanic iron ore often abundant. The glassy groundmass is commonly reduced to very small proportions.

I. The rock is dark and compact, often absolutely black when fresh. The greyer varieties sometimes simulate limestones, but their superior hardness must be noted. The knife produces, however, a light streak on surfaces of basalt. When altered, the rock is softer, with a greenish grey or brown tinge. The joint-surfaces become strongly coated with brown ferruginous products, and a spheroidal structure, as in basaltic andesites, is commonly seen, the successive crusts of the spheroids being removable from one another when decomposition has emphasised the surfaces of separation between them.

In the field, besides this structure, the abundance of straight joints is noticeable; and the basalts exhibit the columnar structure in the most perfect manner, the base of thick lava-flows giving rise to large and more regular columns, while the upper portion is a mass of irregular and curving forms. The meeting of these two

types of columnar rock in the interior of the lava-stream occurs along a plane which appears to divide the mass into two distinct flows; and careful field-examination must in consequence be made before the true upper limit of an old lava-stream can be determined.

Though scoriaceous types are common, glassy structures are very rarely encountered in basalts in the field; but the crusts of some recent basic lavas provide examples of spherulites, perlitic jointing, &c., which repeat all the features of more acid types. The "Variolite" of the Western Alps, Liguria, &c., is a remarkable case of the formation of such crusts on surfaces of basaltic andesites or olivine-basalts. The glass of variolite is now lost by secondary devitrification; but the spherulites remain conspicuous, and form on weathered surfaces the pustular markings from which the rock received its ancient name (*variola* = the small-pox). (See p. 267.)

Basalt dykes fairly frequently show remnants of glass along their planes of contact with the surrounding rock; and sometimes this material has a distinctly vitreous lustre and a thickness of one or two inches (see Tachylyte in division C). The rock becomes rapidly more crystalline from this selvage inwards, until in a few feet it may be practically a dolerite.

The minerals of compact basalt, as may be seen from the classic research of Cordier (p. 110), are difficult to determine with the eye, although the lithoidal mass contains but little glass. The olivine is almost invariably porphyritic, but is lost to view in the dark groundmass on decomposition. When fresh, its striking yellow-green crystals, contrasting with the black prisms of porphyritic augite that may also occur, readily call attention to the basic character of the rock.

The plagioclase, when porphyritic, is often tinged faintly greenish, owing to the general alteration of magnesian silicates round it.

The altered olivine-basalts form part of the old "Melaphyres." Such rocks are very commonly amygdaloidal, owing to the easy decomposition of the basic silicates and the formation of serpentine, zeolites, calcite, and chalcedony in all the vesicles and cavities. The typical colour of these "melaphyres" is green rather than black; others, with extensive oxidation of the iron, resemble the familiar brown-red "porphyrites." When the lime has separated out as calcite, and the soft mass has given way under pressure and become shaly, the "Schalstein" of the Germans is produced ("Spilite" of Brongniart). Many "schalsteins" are derived from basaltic andesites; others from various basic tuffs.

It is impossible to distinguish between many so-called "olivine-diabases" and "melaphyres."

Specific Gravity.—Near 2·9. Lowered by alteration to about 2·8.

Typical Analyses.—A. Pine Hill, S. Britain, Connecticut. Hillebrand, *Bull. U.S. Geol. Surv.*, No. 168 (1900), p. 35. Unaltered rock.

B. Etna, eruption of 1865. Fuchs, *Neues Jahrb. für Min.*, 1865, p. 713.

C. Eichelkopf, Hesse. C. Röthe, 1863, quoted by Roth, *Beiträge z. Petr.*, 1869, p. cx. Porphyritic Olivine visible.

D. Rolandseck. Mitscherlich, *Zeitschr. d. d. geol. Gesell.*, 1863, p. 372. Porphyritic Olivine and Augite.

	A.	B.	C.	D.
SiO_2	52·40	49·27	46·65	44·17
TiO_2	1·08	...	3·10	1·46
Al_2O_3	13·55	18·54	9·57	14·69
Fe_2O_3	2·73	6·98	...	6·78
FeO	9·79	5·62	14·42	4·82
MnO	0·26	...	0·27	...
CaO	10·01	10·38	8·58	10·42
MgO	5·53	3·76	10·05	9·47
K_2O	0·40	2·22	1·76	1·75
Na_2O	2·32	3·45	2·59	2·95
H_2O and loss on ignition	1·67	...	2·06	2·50
Other constituents	0·25	...	...	...
	99·99	100·22	99·01	99·01

II. Typical sections of olivine-basalt show porphyritic olivine (fig. 38), sometimes with purple or brown augite, in a ground-

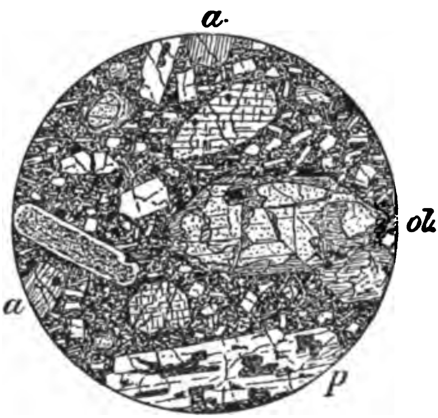

Fig. 38.—Basalt. Lion's Haunch, Arthur's Seat, Edinburgh. × 8. *a*, Augite. *ol*, Olivine, altering along cracks into pale green serpentine. *p*, Plagioclase, often corroded by the groundmass. Some magnetite. Hemicrystalline groundmass, in which the glass is much reduced by the abundant development of microlites of plagioclase and augite.

mass formed by a mesh of plagioclase with interstitial augite granules. Close inspection with high powers reveals traces of glass, containing magnetite (in skeleton-forms) and little globular or rod-like crystallites. This glass is sometimes colourless, sometimes earthy-brown and full of dust-like crystallites. The small proportion which it commonly bears to the crystals is in itself evidence of the basic character of the lavas of this group.

The olivine-basalts easily pass into ophitic or ordinary dolerites (fig. 39).

Magnetite or titanic iron ore is commonly well developed; sphene, except when represented by the alteration-product "leucoxene," is absent.

Rhombic pyroxene becomes rare as the olivine increases. A very pleochroic pale biotite is occasionally met with; but hornblende is particularly rare. The soda-augites are naturally absent, but may re-appear in the basalts containing nepheline, &c.

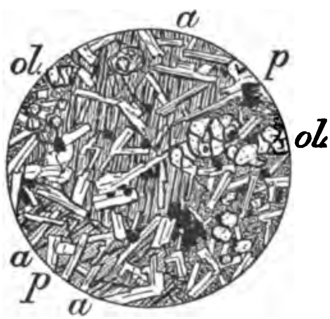

Fig. 39.—Basalt passing into Ophitic Dolerite. Tobermory, Mull. × 25. *a*, Augite, developed around the felspars in large ophitic crystals without defined outlines. In other places, to right and left, the hemicrystalline basaltic groundmass is seen in the interstices of the felspar mesh. *ol*, Olivine. *p*, Plagioclase; small prismatic habit characteristic of basalts. Magnetite also occurs.

In the more altered types ("melaphyres") the pseudomorphs after olivine must be looked for, and appear yellow-brown, olive-green, or almost black through separated iron-oxide. A quantity of isotropic to cryptocrystalline green or yellowish matter occurs between the felspars, representing altered pyroxene and glass. The former extent of the glass is thus very often difficult to trace. Epidote and calcite arise freely in these types, often within the felspars, and zeolites form fibrous aggregates in the cavities.

Varieties of Olivine-Basalt.—Basalt rich in Olivine. In some of these rocks the olivine is seen to be very abundant when a hand-specimen is examined, the yellow-green porphyritic crystals being conspicuously set in a dark groundmass. In others, as at Dreis, Eifel, nodules of olivine and rhombic pyroxene, some 6 cm. in diameter, lie embedded in a normal compact basalt.

Nepheline-Basalt ("Nepheline-Basanite" of Rosen-

busch).—In conformity with the common system of nomenclature, we imply by this term a basalt which contains nepheline in addition to its ordinary constituents. The felspar is likely, however, to be diminished; and when its place is entirely taken by nepheline we have an olivine-nephelinite.

Fig. 40.—Leucite-Basalt. Vesuvius. × 12. *a*, Augite, in one instance surrounded by small leucites. *l*, Leucite; two large crystals lie in the upper part of the field. *p*, Plagioclase, associated with small leucites in the dark glassy groundmass.

LEUCITE-BASALT ("Leucite-Basanite" of Rosenbusch).—This is a common lava of Vesuvius. The leucites are typically conspicuous and porphyritic, the plagioclases being small and rod-like in the groundmass. Olivine is not abundant. The colour varies from grey to black.

Some leucite-basalts, however, are like the ordinary olivine-bearing types, and the leucite is only to be detected by the microscope.

Typical Analysis.—Lava of Vesuvius, 1867-68. Specific gravity, 2·791. Fuchs, *Neues Jahrbuck für Min.*, 1869, p. 79.

SiO_2	46·94
Al_2O_3	21·35
Fe_2O_3	7·27
FeO	4·96
MnO	trace
CaO	9·69
MgO	3·78
K_2O	5·57
Na_2O	1·62
	101·18

HAÜYNE-BASALT.—Many rocks so described may be classed as haüyne-andesites. The haüyne may be porphyritic, or may be minutely distributed in the groundmass in the place of prisms of felspar.

SUPPLEMENT.

The **Olivine-Nephelinites, Olivine-Leucitites,** &c., form a small group; but there are some singular rocks among them, notably the so-called "Melilite-Basalts," which consist largely of melilite and olivine. They yield only 30 per cent. of silica, and are thus extremely ultrabasic.

Melilite cannot be regarded as a common rock-forming mineral; but it may be seen in the hollows of some lavas with the naked eye as well developed brown and gummy-looking tetragonal prisms. At Capo di Bove, near Rome, there is a remarkable lava, with 46 per cent. of silica, in which the melilite ophitically encloses small leucites. In sections, the melilite thus appears as a colourless to pale yellow ground, with a refractive index as high as that of topaz. In other rocks it may be prismatic.

Limburgite (Rosenbusch, *Neues Jahrb. für Min.*, 1872, p. 35, from Limburg in the Kaiserstuhl area, near Freiburg-im-Breisgau. Synonymous with Möhl's "Magmabasalt").—*Structure*—Lithoidal to glassy, with porphyritic ferro-magnesian minerals. *Constituents*—1, Pyroxene; 2, Olivine. Magnetite, titanic iron ore, and apatite are very common. Lithoidal or glassy groundmass.

I. This rock graduates in the field into one in which felspar has developed, and Prof. Bonney has recently shown (*Geol. Mag.*, 1901, p. 412) that its true alliance is with the olivine-basalts. The rock of Rolandseck (analysis on p. 259) provides a link between the latter and the ultrabasic limburgites. Limburgite differs from the peridotite group in the low percentage of magnesia. Rosenbusch's "Augitite" is a limburgite without olivine.

Specific Gravity.—A rather glassy example gave Rosenbusch 2·829.

Typical Analysis.—Limburg. Rosenbusch, *loc. cit.*, p. 54.

SiO_2	42·78
TiO_2	0·28
Al_2O_3	8·66
FeO	17·96
MnO	·95
CaO	12·29
MgO	10·06
K_2O	0·62
Na_2O	2·31
H_2O	3·96
	99·87

II. In sections the glass is strongly brown, and may contain numerous skeleton-crystals of magnetite. The abundance of porphyritic crystals of augite is the most striking feature.

VI. Hemicrystalline Peridotite Group.

Owing to the ready crystallisation of peridotite-magmas, these rocks are little known, and require a determination of at least silica and magnesia for their correct appreciation.

C. Highly Glassy Rocks.

In the field there is little difficulty in comparing with their lithoidal relatives rocks in which the constituents have not separated out from the glassy magma. But such rocks in isolated hand-specimens are incapable of accurate determination. The porphyritic crystals, belonging to a previous period of consolidation, may be widely scattered and afford no clue. Chemical analysis of the glass, with or without the crystals, or even ordinary flame-reactions, will give a fair idea of the potentialities of the individual specimen; but the holocrystalline type, of which it is, perhaps, merely a selvage, may prove to be of more basic character than the glass itself suggests. When the mode of occurrence and the alliances of the specimen are known, it may be described as rhyolite-glass, andesite-glass, &c., when fairly free from crystallites; or as rhyolite-pitchstone, andesite-pitchstone, &c., when the development of these minute bodies has imparted a resinous lustre to the mass. The term Pitchstone is thus retained in a wide and really textural signification; the fact that such rocks are commoner among acid lavas did not prevent the earlier writers from speaking of the passage of basalt into pitchstone.

The pitchstone-condition of igneous rocks may be brought about by the commencement of secondary devitrification as well as by the presence of primary crystallites. In such cases microscopic sections will often show how the crystalline particles have arisen along cracks, such as the perlitic joints, instead of being uniformly diffused or drawn out in bands throughout the mass, as occurs when they are of primary origin.

When it is impossible to use accurate prefixes, the highly glassy rocks may be conveniently classed under one of the following groups, *i.e.*, merely as obsidian or tachylyte.*

* For the behaviour of some natural glasses on treatment before the blowpipe, see p. 104.

I. Obsidian Group.

Obsidian is an old term, said by Cæsalpinus to be derived from Obsidius, the discoverer of the rock. It may be applied to the more highly silicated glasses; these are also fairly rich in alkalies. Their common characters are a low specific gravity, a marked conchoidal fracture, a high fusibility (about 5), and colourless or pale sections in which magnetite is not conspicuous. Small splinters are commonly transparent, not merely translucent, on thin edges.

Perlitic or columnar jointing occasionally interferes with the broad conchoidal fracture. The larger joint-surfaces are usually dull and stained with brown limonite, and the banded or other structures can be well seen upon them. Fragments of lithoidal or glassy lavas, often from other portions of the same flow, are common as enclosures in the glass.

Rhyolite-Glass.—I. This is the most completely vitreous rock in nature, and forms the obsidian of Lipari and the Yellowstone Park. It is black or greenish in mass, like bottle-glass, and is almost colourless in thin splinters. Some varieties are glossy or almost silky-looking through the presence of minute vesicles, or, when inclining to the pitchstone-type, through abundance of minute crystallites.

When perlitic structure is well developed, as may be seen on the joint-planes, or by the globular forms on fractured surfaces, the rock becomes pale and sometimes pearly in lustre through the presence of the minute cracks. Beautiful examples, often called "Perlites," occur in the Hlinik valley, near Schemnitz, Hungary, and at Sandy Braes, in Co. Antrim.

Rhyolite-glass may contain porphyritic crystals, spherulites, or lithophyses, and will exhibit in the most perfect manner the banded, fluidal, and pumiceous structures. The larger spherulites are often hollow at the centre, probably through the action of fumarole-vapours and permeating liquids, which have had little effect upon the surrounding glass. See p. 98.

The old glasses altered by secondary devitrification cannot be distinguished megascopically from the similarly altered lithoidal rhyolites. In North Wales, as on the east flanks of the Glyder-fawr, the Ordovician obsidians contain hollow spherulites an inch or two across; and the lithophyse-structure is well seen here and in the hill to the north of Conway.

Specific Gravity.—About 2·35.

II. Abundance of colourless imperfect rod-like crystallites (fig. 41), and occasionally of the opaque hair-like curving forms

known as "trichites," characterises sections of rhyolite-glass. As the pitchstone-condition is approached, the microlites are seen to be more numerous and their crystal-outlines can often be determined. They rarely build up anything approaching the skeleton-crystals of more basic glasses, but aggregate into sheaf-like and plumose forms, often of exquisite delicacy. The pale green hornblende microlites forming feathery groups in the pitchstone of Corriegills in Arran are among the best known examples of this axial and curvilinear type of aggregation.

The glassy matrix is colourless to translucent brown, or often colourless with browner bands.

Spherulitic and perlitic structures can be studied admirably in

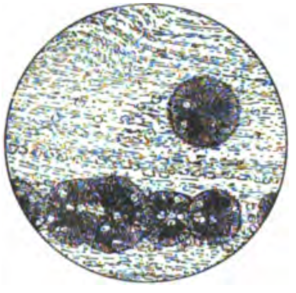

Fig. 41. — Spherulitic Obsidian. Beaver Lake, Yellowstone Park, U.S.A. × 12. Brown spherulites in colourless glass. Numerous microlites in fluidal lines, and minute colourless spherulites, best seen where included in the later and larger ones.

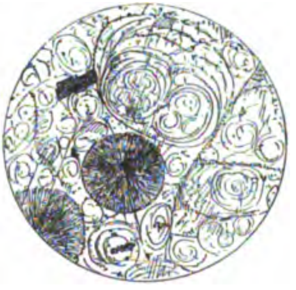

Fig. 42.—Altered Spherulitic Obsidian ("Pyromeride"). Wuenheim, Vosges. × 7. Various types of perlitic structure are seen in the devitrified but once glassy matrix.

rhyolite glass, and they frequently occur together. The perlitic obsidians of the Wrekin area, devitrified by secondary action, have been figured by Mr. Allport (*Quart. Journ. Geol. Soc.*, 1877); and the typical "pyromeride" of Wuenheim in the Vosges (fig. 42), with reddish spherulites and perlitic matrix, can be exactly paralleled among the glassy rocks of Hungary. (See p. 244.)

Trachyte-Glass.—I. Like rhyolite-glass in most respects, but with typically a higher specific gravity (= 2·4), and a greater tendency to the production of pitchstone-types. Ischia provides many examples.

II. Quartz is rare as a porphyritic constituent, and albite and oligoclase become common. Glassy matrix and structures as in rhyolite-glass.

Andesite-Glass in part.—The typical glass of the rhyolitic and trachytic andesites may rank as obsidian; that of the basaltic andesites is tachylytic.

I. Though the pumiceous types are not distinguishable from those of trachyte or even rhyolite, the glasses are less pure and are duller in lustre. They are, moreover, rarer in the field, and even the pitchstone-types contain so many well developed crystals that they readily pass into a lithoidal condition with mere "intersertal" glassy interspaces.

Specific Gravity.—About 2·5 to 2·6.

II. The porphyritic crystals are plagioclase, soda-augite, and occasionally enstatite, often with biotite and more rarely hornblende. A mesh of felspar microlites may be seen developing in the groundmass and foreshadowing the "felted" appearance so characteristic of lithoidal andesites. Spherulites, and other structures inconsistent with the formation of abundant individualised crystals, are rarer here than in the glasses previously described.

II. Tachylyte Group.

Breithaupt * proposed this term for a basic glass—treated by him as a mineral—from the Säsebühl near Göttingen, the word indicating "rapidity of fusion" before the blowpipe. Despite frequent misspelling, the "y" in its termination (ταχύς and λυτός) should therefore be preserved. The name appears to be synonymous with the "Gallinace" of old authors—a term known to Faujas St. Fond in 1778, and derived from the gallinazo, a black carrion bird of the Andes. The tachylytes are basic glasses, and are naturally of more limited occurrence than the members of the obsidian group. Their common characters are a fairly high specific gravity, abundant close-set joint-planes, a low fusibility (about 2·5), and dark-coloured or even opaque sections. Small splinters may show neither transparency nor translucency. They become soft by hydration, producing an altered mixture of silicates styled "Palagonite;" when fresh, however, they are as hard as obsidian (= about 6).

Andesite-Glass in part.—The glass of basaltic andesite falls here.

* *Kastner's Archiv für die gesammte Naturlehre*, Bd. vii. (1826), p. 112.

I. This material, even in the pitchstone-condition, is rare, but may be found on lava-surfaces and in some dykes. The colour is deep brown to black, but the surface only occasionally attains the high vitreous lustre of obsidian. Certain interesting hypersthene-andesite-glasses from Hungary show red-brown spherulites in an almost dull black ground. These spherulitic types possess additional importance on account of their resemblance to the "variolite" of the Western Alps, Anglesey, &c.

"Variolite" is, in fact, a form of spherulitic andesite-glass or basalt-glass, altered by secondary devitrification. It is dark green (or rarely grey-brown) with light greenish white spherulites, which are sometimes 2 cm. in diameter. In the typical area of Mont-Genèvre, near the source of the Durance, it occurs very extensively as a selvage to the surfaces of much altered andesitic or basaltic lavas. In most collections pebbles of variolite occur, which have been gathered in the rivers of the Hautes Alpes. On some of these perlitic structure may be noticed, the cracks appearing of a lighter green tint through the development of epidote.

Specific Gravity.—About 2·65.

II. The features of the andesitic obsidians are found here in an exaggerated form, and crystallisation is carried to a farther extent. Perlitic structure is decidedly rare. The "pitchstone" of Eskdale in Dumfries is an approach to andesitic tachylyte, and is full of well marked felspar crystals (see fig. 36, B).

The spherulitic varieties repeat the general characters of the corresponding acid rocks; but the spherulites, which are brown in section, may often appear complex, as if built up of rays of different composition. This view is supported by the different extinctions of adjacent rays or sectors. The constituents of the spherulites are markedly pleochroic.

The glass is typically a yellow-brown, a colour sometimes retained in the palagonitic altered examples (fig. 22, p. 196). Most of these are, however, green; they show a faint effect between crossed nicols, owing to the double refraction of the hydrous constituents. By development of magnetite dust and minute aggregations of dark crystallites, the glass may become practically opaque.

The variolitic varieties, corresponding to the "pyromerides" of the acid series, have a greatly altered groundmass, in which epidote is extensively developed. The spherulites consist of delicate feathery and branching rays, and lose their sharp boundary in specimens collected about 5 cm. from the original surface of cooling of the rock. As this ancient glass passes into the lithoidal

mass of the lava, areas of radially arranged felspar, which are sections of spherulitic groups, take the place of the typical spherulites in the slide.

Olivine-Basalt-Glass.—I. This is the typical tachylyte, and may contain porphyritic olivine in the most basic examples. It occurs as lava-crusts, scoriaceous or compact (as in Hawaii), or as a selvage to dykes (as in the Western Isles of Scotland). It has a vitreous to resinous lustre, and is black or blue-black, with dull brown joint-surfaces. These are often so numerous that the true character of the rock appears only on artificial fracture. The typical glass is barely translucent, and the abundance of magnetite dust in some examples makes their powder magnetic. The easy fusibility must be noted.

Dull brown spherulites occasionally appear. Scoriaceous slaggy types are common among modern lava-surfaces; but pumiceous types are very rare. The "thread-lace scoria" of Hawaii and the filaments of "Pélé's Hair" show, however, how complete a glass can occasionally be formed from olivine-basalt. The basalt-glass of Hawaii forms a scoriaceous crust some 2 inches thick upon the lavas, and a crust resembling bottle-glass upon those in the crater of Kilauea. Lava-flows of glass, comparable to the obsidian-streams of the Yellowstone, must not be expected in the basic series.

Variolitic representatives of olivine-basalt-glass occur in Anglesey and Co. Down. See Andesitic Tachylytes above.

Specific Gravity.—About 2·7. Sometimes as high as 2·9.

II. The microscopic characters repeat those described under the andesitic tachylytes. Crystallites of magnetite grouped in crosses, and other skeleton-crystals, are abundant in the brown groundmass, and spherulitic and sheaf-like aggregates are common. When the magnetite is aggregated into little octahedra, the glass may be clear brown and translucent; but when it is finely disseminated as dust, only the porphyritic crystals can be seen in an absolutely opaque black groundmass. Reflected light may reveal in such cases spherulitic or other structures.

The porphyritic crystals may be as intensely corroded as those in many andesites. Olivine is abundant as a porphyritic constituent in many basalt-glasses from Hawaii.

The microscopic appearance of "variolite" has been touched on above among andesitic types. The yellow or green "palagonites" often represent olivine-basalt-glass.

Peridotite-Glass.—Chemical analysis must be resorted to before a tachylyte can be safely referred to peridotite. It may be possible, however, in the field to trace some examples

into practically holocrystalline rocks consisting of pyroxene and olivine only.

Specific Gravity.—About 2·85.

Note.—The glass of the nephelinites, leucitites, &c., is so little known as to demand no separate description.

Finally, it may be useful to indicate in a general table the grouping adopted for the igneous rocks in the foregoing pages. The great and important names are printed in **thick type**; those of rocks with both felspar and a felspathoid in SMALL CAPITALS; and those of the rare rocks, in which the felspathoid entirely takes the place of the felspar, in *italics*. Nepheline is used in the table as the representative of all the felspathoids. (See next page.)

TABLE OF IGNEOUS ROCKS.

Holocrystalline Type.	Hemicrystalline or Glassy Representative.
Granite. **Eurite (Quartz-Porphyry).**	**Rhyolite.**
Syenite. **Compact Syenite.**	**Trachyte.**
NEPHELINE-SYENITE. COMPACT NEPHELINE-SYENITE.	NEPHELINE-TRACHYTE (NEPHELINE-PHONOLITE).
Quartz-Diorite. **Quartz-Aphanite.**	**Rhyolitic Andesite.**
Diorite and **Gabbro.** **Aphanite** and **Dolerite.**	**Trachytic** and **Basaltic Andesites.**
NEPHELINE-DIORITE. NEPHELINE-APHANITE.	NEPHELINE-ANDESITE (TEPHRITE).
Nephelinite.	*Hemicrystalline Nephelinite.*
Olivine-Gabbro. **Olivine-Dolerite.**	**Olivine-Basalt.**
NEPHELINE-OLIVINE-GABBRO. NEPHELINE-OLIVINE-DOLERITE.	NEPHELINE - OLIVINE - BASALT (NEPHELINE-BASANITE).
Olivine-Nephelinite.	*Hemicrystalline Olivine-Nephelinite.*
Peridotite. **Compact Peridotite.**	**Hemicrystalline Peridotite.**

CHAPTER XX.

METAMORPHIC ROCKS.

THE definition of a metamorphic rock must always be a matter of opinion. We include here those rocks in which new crystalline developments, or new structures, or both, have arisen under the influence of subterranean heat, or pressure, or actual earth-movement.

From this point of view such rocks as "epidiorite" and "flaser-gabbro," and many of the Welsh devitrified obsidians, should be treated as metamorphic. We must refer back to these, and also closely compare our notes on consolidated sedimentary masses with the present remarks on their more altered representatives.

Foliation is the structure most commonly to be met with in truly metamorphic rocks. In fine-grained materials cleavage may arise, often as a prelude to foliation. Brecciation, and the drawing-out of the fragments into folia by earth-movement, are closely allied processes, and the rocks resulting from these operations may be found passing into one another in the field.

A. Rocks affected by Contact-Metamorphism.

The embryo-crystals and ill developed forms in these baked and altered sediments give considerable trouble in determination. The crystals are often far more vague under the microscope than in the rock-mass, since their boundaries shade off imperceptibly into the amorphous or granular groundmass, while they contain so much uncrystallised matter as to present no clear optical characters. The groundmass may be fused in places to a glass, as is the case with the cement around the sand-grains in some altered sandstones; or it may appear practically earthy and unaffected. Signs of cleavage, or even a foliated structure, are apparent when the minerals have developed along definite planes in the rock, which are often, in cases of mere contact-alteration, the

original bedding-planes. Some beds may be found to have been more susceptible to mineral changes than others in the same series.

Spotted Shale.—I. The shaly mass is full of dark brown or black spots and patches, with an attempt at regular outlines. These are mere "pigment-spots," or actual embryo-crystals, and show no true faces or specific characters. Mere contact with a dyke will sometimes produce this type of alteration in the shales or slates around. At times recognisable garnets may be developed.

II. With the microscope the dark spots may show some signs of cleavage, pleochroism, &c., like the biotite patches in the rock of Tirpersdorf, Saxony. Many remain, however, in a cloudy condition, and remind one of the dusky undetermined matter surrounding spherulites in vitreous rocks. Little patches of garnet may be picked out by their high refractive index and their isotropism.

Slaty Rocks with development of Additional Minerals.—Pyrite, in fair-sized cubes, is a common product near the junction of argillaceous rocks with an igneous mass. Examples may often be seen in Wales, either in the Snowdon or the Cader Idris areas. Mica, light or dark, very readily arises along the divisional planes, and garnets, red-brown and lustrous, are sometimes found. Andalusite and staurolite are frequent, especially the former, neither mineral being well defined in such cases when examined microscopically. Chiastolite is sometimes seen, in long well bounded white prisms, in the dark grey groundmass, as, for instance, on the flanks of the Skiddaw granite.

Secondary quartz generally arises in some portion of the mass, in the form of white knots or veins, and its introduction may have been connected with the hot liquids accompanying the close of igneous action. Small granular secondary felspars may also be developed; and the whole series of changes bridges over the gap between mere contact-products and rocks that might be attributed to the larger processes of regional metamorphism

Baked Shale.—I. A very common form of alteration along the edges of ordinary dykes. The rock, which may be a volcanic ash or a clay, loses its shaly character, and a partial fusion seems to take place. It becomes too hard to be scratched with the knife, breaks with a fairly good conchoidal fracture, and appears like a dull porcelain ("Porcellanite") to the eye. The colour is usually grey or black; a slight effect of iridescence, as from a multitude of minute glancing surfaces, is sometimes noticeable

as the rock is turned about in the hand in sunlight. Some "Lydian Stones" come under this heading.

II. A confused partially melted and recrystallised groundmass appears in section, often with rod-like and hair-like microlites. When the section has traversed the igneous rock and the contact-rock as well, the line between the two is typically sharp; but cases occur where the glassy selvage of the former and the metamorphosed sediment simulate one another. Actual transfusion seems much rarer than one would at first suppose.

Altered Limestone.—A crystalline granular structure may be set up in limestones by contact-metamorphism, and only traces of previous structures, fossils, or of the original colouring, may remain. The magnificent series of silicates developed in the limestones of Monte Somma and in Tyrol, by interaction with volcanic intrusions, is known to all collectors.* Many "Calciphyres" and "Amphibolites" have no doubt been produced by contact-metamorphism, involving sometimes a transference of material from the igneous rock.†

Altered Igneous Rocks.—The baking of one igneous rock by another is a common phenomenon. Andesites thus become compact and flinty; the surfaces of basaltic flows may become reddened by oxidation, when heated by a succeeding flow; and so on. The most striking changes are, however, produced when the rock penetrated melts at a lower temperature than the invading rock. (See pp. 216 and 225.)

B. Rocks affected by Regional Metamorphism.

Regional metamorphism may result from the heating of rocks on a large scale by an invading igneous mass; in this case, new minerals may be developed along the bedding-planes of sediments, and considerable intermingling of the invaded rock and the invader may occur. In other cases, pressure, acting over a wide area, is the principal agent of metamorphism, and this leads to the granulation of the original constituents, the

* See Mierisch, "Die Auswurfsblöcke des Monte Somma," *Tscherm. Mittheil.*, 1886, p. 113. Messrs. Gregory and Lavis have carefully studied the origin of the serpentinous limestones of the same area, and have compared their structure with that of the supposed fossil *Eozoön* (*Sci. Trans. R. Dublin Soc.*, ser. 2, vol. v., 1894, p. 259).

† See discussion in G. Cole, "Metamorphic Rocks in Tyrone and Donegal," *Trans. R. I. Acad.*, vol. xxxi. (1900), p. 460.

deformation or reconstruction of them as lenticular folia, and frequently the entire recrystallisation of the mass.

The microscope must often be called in to determine if the foliation of a metamorphic rock is accompanied by evidence of earth-pressures; and the possibility of crystallisation under pressure without movement must also be borne in mind. In dealing with metamorphic rocks, the evidence obtained in the field is of the very first importance. Even here, the numerous folds, faults, and thrust-planes accompanying foliated masses allow several opposed explanations to be put forward whenever a section appears to show the continuity of a fossiliferous sediment with a schist. The study of deformed and crushed, but truly fossiliferous, deposits cannot fail to be of the greatest service in this connexion.

I. Crystalline Limestones.

The majority of the "Marbles" come under this heading. The limestones of metamorphic areas become distinctly crystalline, and the grains of calcite may attain a diameter of 3 or 4 mm. Where, however, crushing has accompanied the change, the individual crystals are reduced in size, and the rock becomes compactly microcrystalline. The crystallisation, and perhaps partial removal, of the non-calcareous matter leave the calcite mass often marvellously pure, as in the famous statuary marbles. At other times, as in the central Highlands, the rock is typically grey, but can at once be distinguished by its softness from any associated grey quartzites. Dolomites in a similarly highly crystalline condition must be tested with hot acid. Specimens of crystalline alabaster (see p. 208) must be compared with statuary marbles, and the difference of hardness and specific gravity noted.

Serpentinous veins traverse many of these marbles and give them a tinge of yellow-green. In some cases the limestone or dolomite becomes so permeated, and its original condition so obscured, that it must be classed merely as an "ophicalcite." Such masses may have resulted from the destruction even of igneous rocks containing calcic and magnesic silicates.

Secondary minerals are to be seen in some limestones with the naked eye. The "Cipollino" of the Italians is rich in flakes of silvery mica, or sometimes of a brilliant green chromium-variety. Brongniart's conveniently named "Calciphyres"*

* *Classif. minéral. des roches mélangées*, 1813, p. 38.

may contain tremolite, diopside, wollastonite, scapolite, grossularite, and even felspar.* In treating the rock with acid, it must be remembered that some of these silicates may be destroyed. They commonly stand out, however, on weathered surfaces.

II. The calcite granules are seen to be closely packed together, and often interlock with one another and assume irregular boundaries. Twin-lamellation is conspicuous. In dolomites this is absent, and sections of distinct rhombohedra are usually seen (Pl. II., figs. 1 and 2). The accessory silicates in the calciphyres are typically colourless in section; but the polariscope reveals them by their tints, which are much lower than those of the calcite. Serpentinous limestones often show ovoid residual grains of olivine (? monticellite). The minerals developed in limestones in the neighbourhood of volcanic vents prepare one for the most remarkable associations of silicates in these more extreme metamorphic types (p. 273), and, by interaction with a slowly cooling igneous mass, even amphibolites may become built up on a fairly regional scale.

II. Quartzites.

I. Prof. Bonney has pointed out how the most altered forms of quartzites arise from sandstones that were originally pure, the deposition of new silica, and the consequent interlocking of the grains into a uniform whole, being impeded by the presence of clayey or other foreign matter. We have already described, under Sandstones, the ordinary characters of these cemented types. In metamorphosed areas, quartzites may resist the forces which cleave the surrounding masses or which convert them into foliated rocks; and they may thus be useful as a clue to the original stratification of the district. By their superior hardness and their composition, they stand out in white or grey bands and bosses among the more easily decomposing schists.

Mica often occurs in quartzite, and, by its primary pre-

* Issel reports the discovery of albite crystals which have formed round Radiolarian skeletons in a limestone of Tertiary age. *Comptes Rendus*, 24 Février, 1890, and *Ann. del Museo di Genova*, p. 91, pls. v. and vi.

sence or its development, allows of a foliated structure. The rock may thus break along new planes which are rendered lustrous, commonly by a pale silvery mica. The most beautiful and regular development of this schistose structure is to be seen in many "flaggy gneisses," which split like finely laminated sandstones, and which consist almost entirely of quartz and mica. The delicate divisional bands formed by the latter may sometimes represent stratification; but they may also result from movement under pressure, and must be compared in the field with similar planes in the adjacent masses.

II. In truly metamorphic quartzites the deformation of the rock and its partial crushing are traceable in microscopic slides. Individual grains show bands and waves of colour when the section is rotated between crossed nicols, and they are often drawn out into wisp-like forms with irregular boundaries, and are in part broken away and granulated. Lines of liquid-enclosures often run through from grain to grain in fairly parallel planes across the rock, solution of the interior of the crystals having taken place, perhaps as a prelude to actual shearing. (Compare fig. 19*a*, p. 140.)

The grains of felspar and other bodies in quartzites derived from grits are similarly distorted, and they may be surrounded by a zone of comminuted fragments. Some parts of the rock have at last given way altogether, and a fine-grained quartz-schist has resulted, with delicate foliated effect. These crushed and rolled out portions may appear in a remarkable manner in a section, side by side with the coarser granular type of rock.

Cracks abound, but are filled with chalcedony or a fine mosaic, which is, indeed, a sort of microscopic granular fault-rock.

III. Cleaved Rocks.

Slate.—I. This is the typical cleaved rock, since only fine-grained masses, in which the minute constituents are plate-like or acicular in character, can develope the structure with such perfection. The stratification, shown by "stripes" of a different grain or colour, must be sought for in the field, since cleavage and lamination rarely correspond. The common colours of slate, as is well known, are blue-black, purplish, and greenish. Minute mica scales may develope along the cleavage-planes,

and a wrinkling of the latter at the same time produces the link with mica-schist, called "Phyllade" by d'Aubuisson, and "Phyllite" by many authors.

The distortion and gradual obliteration of fossils in slates are interesting points for study. The original "clay-galls" and nodules similarly become ovoid, and their longer axes no more lie in the planes of bedding. Small faults are commonly seen in slates which show "stripe." (See Teall, *Geol. Mag.*, 1884, pl. 1.)

Iron pyrites is a common accessory. Magnetite is probably frequent, but its little grains are obscured by the dark colour of the rock.

In the field there is often difficulty in realising, on looking at a great cliff-wall of slates, that the cleavage-planes are not those of stratification. They are here and there emphasised by weathering, and iron-rusts form in places so as to mark out particular planes. Hence a false appearance of bedding may be produced, particularly at a distance. Any hard bed, especially sandstone, deposited among the original shales, will readily correct such an impression (p. 275).

II. In sections, all the transparent microlites and grains seem lying with their longer axes parallel to one another. Of course these may have a yet longer axis in a direction oblique or perpendicular to the plane of the section; but in cases where a creep or flow of the materials has occurred, a section is possible which shall practically show each particle with its maximum elongation. (See p. 135.)

The impure and darkened groups of kaolin-flakes, or plates of mica, are pressed out or develop as extremely flattened lenticles, so that, when cut perpendicularly to the cleavage-surfaces, fine dark lines run parallel and close-set through the slide. By reflected light any grains or crystals of iron pyrites and magnetite are easily seen. (Pl. II., fig. 3).

The transparent constituents consist very largely of mica. Rutile seems invariably present, and titanium dioxide commonly forms, as shown by analyses, ·50 per cent. to ·95 per cent. of the rock. References to detailed papers on slates by Mr. Hutchings are given on p. 199.

Many slates result from the action of pressure on volcanic ashes. The minute pumiceous particles are often traceable, and larger crystal-grains occur, some of which contain intruded glass, as an indication of their volcanic origin. When the material ejected is of basic character, it will be altered to yellowish streaky products and is very likely to be unrecognisable. Even

in such cases, fragments of the porphyritic crystals may appear in a suggestive manner.

IV. Distinctly Foliated Rocks.

This group includes the schists and gneisses, the origin of which has been so widely discussed in recent years. The fact that such rocks may arise at any period in the earth's history is now generally recognised. The so-called "fundamental gneiss" of many areas has again and again been shown to be intrusive in still earlier sediments; while composite gneisses are fairly common, which result from the intrusion of sheets of igneous rock between the foliation-planes of an earlier schist, or even the bedding-planes of a sediment. Rosenbusch (*Elemente der Gesteinslehre*, 1898, p. 467) uses the term "orthogneiss" for gneisses derived from igneous rocks, and "paragneiss" for those formed from undoubted sediments. English writers use the word "schist" for all well foliated rocks falling short of the coarser and more felspathic type termed "gneiss." It must be remembered that the French "*schiste*" and the German "*schiefer*" include, in addition, rocks where the lamellar structure is due to bedding, and where no secondary mineralisation has gone on.

In the field these rocks form a most fascinating study, since they are associated with the finest mountain-scenery, and assume, when unglaciated, the boldest and sharpest outlines. But the correlation of closely adjacent portions of the same rock-wall must be undertaken with the utmost caution, owing to the intricacies of faults and thrusts. As Prof. Lapworth has again and again pointed out in the N. W. Highlands, metamorphic masses may result from the mingling together of pieces of completely different formations, so that they cannot be styled "altered Cambrian," "altered Silurian," or so forth, but possess no age other than that of the crushing and rolling processes to which they have been together subjected.

Numerous schists and gneisses result from the deformation of rocks already holocrystalline, that is to say, of aphanites, dolerites, or granites. Such deformation is accompanied by some mineral changes; but the ultimate bulk-analysis of the rock may remain much the same. The margins of igneous masses or dykes in all contorted or faulted areas are likely to show signs of such alteration, and intrusive basic sills are often converted into hornblende-schist.

Plate II.

METAMORPHIC ROCKS.

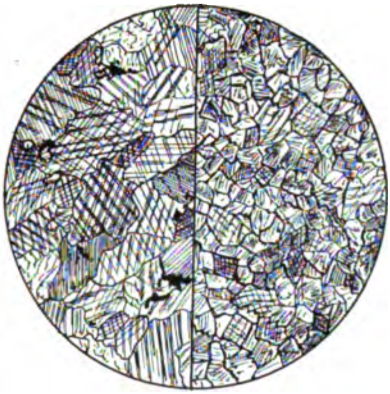

Fig. 1. Fig. 2.

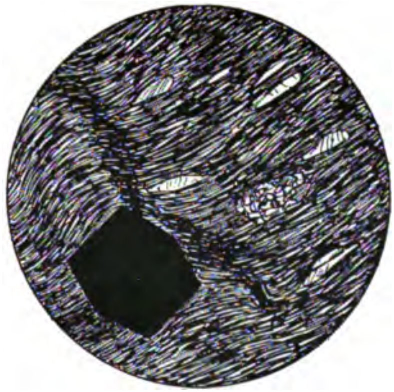

Fig. 3.

Fig. 4.

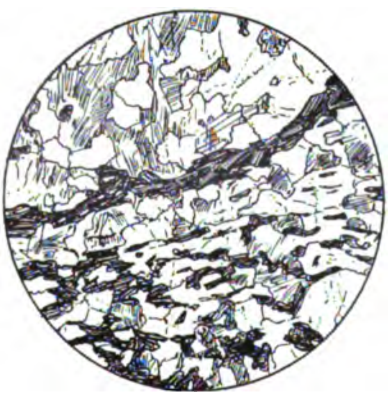

Fig. 5.

Fig. 1.—Crystalline Limestone (calcite). Letterbreckan, Co. Galway. × 12.

Fig. 2.—Crystalline Dolomite. Near Giessen, Hesse. × 12.

Fig. 3.—Slate (Phyllite type), with pyrite and white mica. Easdale Id., Argyll. × 12.

Fig. 4.—Gneiss formed from crushing of previously fluidal granite, producing mylonitic bands. Carbane, Glenties, Co. Donegal. × 9.

Fig. 5.—Gneiss formed by intrusion of aplitic granite along the foliation-planes of biotite-schist. Craignayarrow, Co. Tyrone. × 9.

The division of foliated rocks into altered sediments and altered igneous masses is beset with such enormous difficulties that we must be content merely to bear in mind the possibility of either origin, and to seek diligently for elucidation in each case as it comes before us in the field. There is, however, a growing feeling that the great majority of amphibole- and chlorite-schists, a few mica-schists, and many gneisses, have their origin in igneous rocks; while in many cases original flow, and not metamorphism, is responsible for their special structures. (Compare p. 102.)

We should note that microscopic sections of foliated rocks should be taken perpendicularly to the edges of the folia.

Sub-group 1—Schists.—These are rocks in which the foliation is little interfered with by large crystals, and in which the difference between the mineral constitution of successive layers is not so marked as in the coarser gneissic type. The folia are often intensely crumpled; but separation of the rock occurs parallel to their surfaces rather than along other divisional planes. When garnets, &c., are developed during metamorphism, they cause the foliated materials to fold over and flow round them, so that the obstacle, with the curving layers meeting again on either side of it, resembles an eye. This gives the "eye-structure," which is seen on fractured surfaces perpendicular to the foliation-layers, and which is far more strikingly developed in the gneisses.

Prof. Lapworth has styled "mylonitic" (μυλών, a mill) those cases where, in section, the larger lenticular constituents are surrounded by a cryptocrystalline or amorphous paste, itself lying in "a flowing microscopic tissue of opaque fibres and strings," as if the whole had been ground to flour between millstones. Such "mylonitic rocks are compact and slate-like."

Finally, we must be prepared for rocks, truly stratified, which simulate schists, from the fact that their materials are derived from the weathering away of truly metamorphic rocks.

Mica-Schist.—I. This is by far the commonest metamorphic rock. The lustrous folia of mica, now in broad swelling curves, now wrinkled, now bent into the sharpest folds, disguise the other constituents and appear to constitute the mass. The mica is generally a pale species, and rarely appears black. Quartz can generally be detected, sometimes in great segregated nodules or in veins. Garnet, red and well seen on fracture, is almost always present, and forms little "eyes" in the foliation.

The use of the thumb-nail will distinguish fine-grained mica-schist from talc-schist, in addition to the higher lustre of the

mica. With the knife the peculiar grating sound of the mica surfaces can easily be detected.

Sillimanite is frequently present, giving dull white fibrous patches, in schists altered by igneous contact. Andalusite or kyanite may occur in such rocks, the latter showing its blue tint when the hammer crushes it.

Typical mica-schist has a silica percentage of about 60.

II. The mica is most commonly colourless, with strings of ill-defined greenish and greyish matter interfoliated with it. Granular quartz and some felspar, often arranged in streams, occur. The eye-structure due to the presence of garnets is excellently seen in sections (fig. 43). Fibres of sillimanite often penetrate biotite and quartz.

Fig 43.—Mica-Schist. Saxony. × 7. *g*, Garnet, pale pink, and showing signs of cleavage. *m*, Colourless Mica, bent and drawn out in the direction of the foliation-layers. *q*, Quartz, granular, and often elongated parallel to the foliation-layers.

In fine-grained examples a double wrinkling and foliation may sometimes be traced, arising at two distinct periods of pressure and movement.

In examining the slide we must never forget the solid; the sections of mica, for example, are cut from extended lenticular patches, the union of their basal surfaces constituting the glancing folia of the rock.

Chlorite-Schist.—I. This is quite a rare rock compared with the preceding. It is dark green, with black-green scales on the surfaces of foliation, and is typically rather fine in grain. The softness is characteristic, the whole having a soapy feel in the hand. In the field the absence of the glancing surfaces of mica, and the general darkness of the rock exposed, mark it out from mica-schist.

Magnetite is the commonest accessory, the rock being very poor in silica (perhaps as much as 30 per cent.). The octahedra of magnetite, black and metallic, are often beautifully developed in the green scaly groundmass, and are sometimes surrounded by a spherulite of radial chlorite, which looks like a rosette when fractured.

Veins and little patches of epidote may occur.

II. The chlorite appears in flakes and fan-like groups; the

cleavage of the mineral is irregular and much disturbed. Magnetite is identified by reflected light. Small brown rutiles very commonly occur.

Serpentine-Schist.—I. This is a common rock in some mountain-districts, such as the Western Alps, and is derived, in a great number of instances, at any rate, from the crushing of altered peridotites. The colour is dull green, lighter than that of chlorite-schist; sometimes blue-green or purple. The foliated surfaces are soapy-looking, and bent in fairly broad folds; slickensides abound. The rock, indeed, breaks in the field along joint-surfaces and slickensides quite as often as along the planes of foliation.

Some few serpentine-schists can be traced into more normal types of schist, and appear to result from the permeation of aluminous schists by serpentinous matter. The percentage of silica in serpentine-schist is about 40.

II. Sections generally show excellently the folding and movement undergone by the soft yielding rock. The whole field is a pale transparent green. Garnet, epidote, and magnetite may occur.

Talc-Schist.—I. A somewhat rare magnesian schist, light in colour, generally pale greenish or pure white, with a silvery and pearly lustre. The rock feels soapy to the hand, and its hardness = 1.

Quartz grains and patches often occur, and needles of actinolite may be scattered on the foliation-surfaces.

The silica percentage rises at least to 55, being reduced from that of pure talc by presence of mica, &c.

II. The talc is more easily distinguished in the mass than in section. Quartz granules form quite a mosaic along certain bands, and are commonly abundant.

Amphibole-Schist.—Many "Amphibolites" come here.

I. Next to mica-schist, **Hornblende-Schist** is one of the commonest metamorphic rocks, and results in very many cases from the foliation of altered basic igneous rocks. The rock is commonly green-black, with a lustre due to fibrous or somewhat plate-like hornblende, quite distinct from that of a dark mica-schist. The layers of hornblende, which are less crumpled than those of mica-schist, may alternate with thin lighter bands of felspar, quartz, and sometimes epidote. Dark mica is an accessory, and often arises from the action of invading granite on the amphibole of the schist.

The rock breaks more readily along joints, and more evenly on cross-fractures, than mica-schist, since the materials are granular and idiomorphic rather than spread out into lenticles.

In the field, dolerites and aphanites can be seen to pass into

hornblende-schist, the rock being often only an extreme type of "epidiorite."* Even coarse gabbros, after some intermediate stages of mineral change, become rolled out into an almost mylonitic condition and form granular hornblendic schists.

The silica-percentage is about 50.

II. The hornblende is small; granular or idomorphic; sometimes fibrous and coarser. The typical cleavages and pleochroism can be seen. Bands of granular clear colourless matter occur, which show between crossed nicols a mosaic of low colours. These consist, in the majority of cases, of granular felspars, as may be determined with convergent polarised light. Twinning can be seen in some of the grains, and they consist of lime- or lime-soda-plagioclase, which has recrystallised in this condition. (See also "epidiorite," pp. 226 and 229.)

Prisms of yellow or colourless epidote, or of zoisite, may be abundant. Pale pyroxene, sphene, and garnet should be looked for. Iron oxides, titanic or not, and rutile, are very common.

The amphibole may extend its boundaries by additions from the metamorphic mixture round it, when subjected to a new stimulus, such as the invasion of a granite magma.

Other Varieties of Amphibole Schist.—ACTINOLITE SCHIST. A pale or bright green variety, of limited occurrence, containing needles of actinolite. The name is sometimes given to a talc-schist with actinolite from the St. Gotthard above Airolo.

GLAUCOPHANE-SCHIST.—I. This rock occurs in very important masses in the southern Alpine valleys, particularly near S. Marcel, in the Val d'Aosta; and it has been found near the Anglesey Monument, on the Menai Straits, by Prof. Blake. Probably it is of wider range, but has been overlooked. Its colour is a characteristic slate-blue grey, deepening almost to black, but distinct from the green-black of common hornblende-schist. The prismatic habit of the glaucophane gives a silky lustre when this mineral is abundant. Faint yellowish veins of epidote traverse the rock, and this mineral is also found throughout the foliation-layers.

II. Glaucophane, with its beautiful pleochroism and prismatic forms, abounds. Pale yellow epidote and quartz are commonly present. Garnet, in pink grains, occurs in the "eclogite" types. Rutile is well developed at St. Marcel.

Eclogite (Haüy, 1822) **and Garnet-Amphibolite.** Consists of pyroxene or amphibole, or both, with garnet. Triclinic felspar

* See particularly Teall, *Quart. Journ. Geol. Soc.*, vol. xli. (1885), p. 133, and *British Petrogr.*, p. 198, plates xix. and xx.

and quartz are usually present in granular forms. From coarse and sometimes schistose types, these rocks shade into the granular pyroxene-diorites and pyroxene-granulites described on pp. 230 and 286. In sections, the pyroxene is usually pale green, while any hornblende present ophitically includes the other minerals. The garnet is often grossularite. The typical mode of occurrence of these rocks is in the form of blocks, large or small, entombed in gneiss or granite. Their connexion with intense thermo-metamorphism may be regarded as certain, and the original rocks, though all were probably rich in lime, may have been of very varied nature.

Calc-Schist.—I. This is the schistose representative of the limestones with accessory silicates, these minerals forming lustrous specks and rods upon the planes of foliation. Most commonly the rock is a schistose "cipollino" (see p. 274), the predominant silicate being pale silvery mica. At Shinness, in Sutherland, amphibole (tremolite, &c.) is developed in calc-schist.

The knife readily detects the true character of the rock. Its colour is white to grey, and its general paleness makes its exposures in the field a contrast to those of the schists associated with it. Since it is far less fissile than ordinary schists, it can be quarried in regular blocks like other limestones. When treating the rock with acid, it must be remembered that calc-schist includes schistose dolomites.

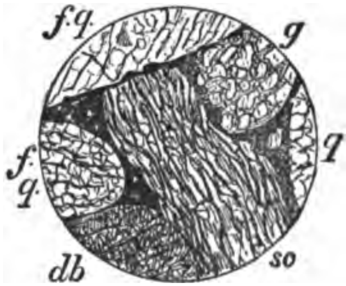

Fig. 44. — **Ancient Conglomerate. Charlton Hill, Shropshire. × 7. *db*, Diabase. *f.q*, Foliated quartzite. *g*, Gritty sandstone with cementing material. *q*, Quartzite. *sc*, Schist, with characteristic outline, unlike the adjoining pebbles, due to its breaking along the foliation-surfaces. This conglomerate, probably itself Pre-Cambrian, gives evidence of the existence of materials which have been metamorphosed at a still earlier date.**

II. Nothing need here be added to what has been said under the head of crystalline limestones (see also fig. 23). The silicates may be examined separately, if necessary, after treatment of the rock with acid.

Quartz-Schist.—Foliated quartzite with mica, &c. (see fig. 44). See account of quartzites, p. 275. Also granulites.

Sub-group 2—**Gneisses.**—While these may be regarded as coarsely developed schists, it is the felspathic element that, by

its prominence, marks them off most distinctly from the foregoing sub-group. There can be no doubt that an immense number of occurrences of gneiss are due to the action of earth-movement upon igneous masses; and the very remarkable work of Lehmann in Saxony and Lawson* in Canada shows how this difficult question may be attacked and investigated in the field. Because a coarse gneiss accompanies and is seemingly interstratified with a series of schists, we must not conclude that it formed part of the original deposits of the locality, since it may result from a series of later parallel intrusions.

Some gneisses owe their foliation to original conditions of consolidation (see p. 102), and are therefore not metamorphic. In sections of such rocks the larger constituents will not be surrounded by mylonitic matter, as in gneisses that have been foliated subsequently to consolidation. On the other hand, modern research seems to confirm the old view that gneisses may be formed from sediments by extreme contact-metamorphism (see Barrow, *Quart. Journ. Geol. Soc.* ,vol. xlix., 1893, p. 343, and Callaway, *ibid.*, vol. liv., 1898, p. 374); in such cases, as well as in those where pressure has operated without movement, strain-shadows and mylonitic envelopes will similarly be absent.

I. The gneisses, through the presence of compact bands or crystal-knots of felspar, quartz, &c., and through the coarseness of the foliation, do not split so readily as schists. A large specimen must often be chosen in order to show the foliated structure. Eye-structure is magnificently displayed, as in our own Hebridean rocks or in the "Protogine" masses of Mont Blanc. Sometimes the white felspar eyes are embedded in a foliated ground of dark mica or hornblende. Where banding occurs, the bands do not consist of layers of distinct minerals, as is very commonly stated, but rather of distinct rock-types. A common and striking form of banded gneiss occurs when granite intrudes along the foliation-planes of a mica-schist, or streaks out in its flow partly digested inclusions of basic rock (Pl. II., fig. 5).

Whatever the origin of the felspar, it clearly existed in a number of cases before the deformation of the mass. All the characters shown by felspar in granitic rocks are repeated among the gneisses. The micas and ferro-magnesian constituents are often quite scanty; but quartz is exceedingly common, both in knots and bands. Large garnets, and sometimes cordierite, occur accessorily.

* "Geology of the Rainy Lake Region." *Ann. Report Canadian Survey* for 1887. See also Seymour, "Metamorphism of an Andesite," *Sci. Proc. R. Dublin Soc.*, vol. ix., 1903, p. 568.

Though occasionally sinking to 60, as in gneisses rich in hornblende or biotite, the percentage of silica is very often above 70. This statement excludes the exceptional basic gneissoid rocks that are produced from diorites and gabbros, often by original flow.

II. The section must be as large as possible. The quartz is in irregular granules, often obviously crushed into a mosaic-condition and spread out into streams. The micas, often biotite, occur in rather small crystals, and their foliated arrangement is much disturbed by the coarse hard crystals over which they are pressed. The larger felspars show microcline structure and cross-twinning in many cases, and are evidently under considerable stress; they may be surrounded by granulated portions removed from them and spread out round them.

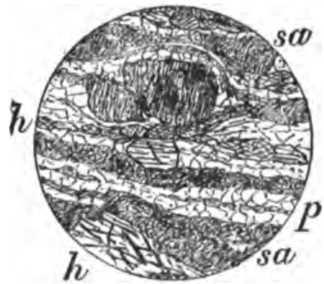

Fig. 45.—Gabbro-Gneiss. Le Chenaillet, Mt. Genèvre, Hautes Alpes. *h*, Secondary hornblende, often in bands and strings of crystals. *p*, Granular secondary Plagioclase, forming colourless layers. *sa*, Original Plagioclase, now "saussuritic," and forming occasional "eyes," like that in the upper part of the field. Foliated structure.

In fact, the characters of a deformed igneous rock are again and again displayed in sections (Pl. II., fig. 4).

Cordierite, when it occurs, must be first studied in the rock itself. Its sections are full of bent and tuft-like fibrous inclusions of sillimanite.

Varieties of Gneiss.—Gabbro-Gneiss (fig. 45).—This is a type of many gneissoid rocks found, as above remarked, on the margins of true igneous masses. The diallagic pyroxene is reduced to brown knots and eyes, with a stream-like development of secondary amphibole formed round it and connecting the residual crystals one with another. The felspar, which has already become saussuritic in the true gabbro, is drawn out into foliated bands, and more transparent secondary granules have arisen, as in so many epidiorites.*

Almost all gneisses, however, resemble metamorphosed granites or quartz-diorites. More complete knowledge may show us that

* Roth regards many of these diallage-plagioclase rocks as non-eruptive, and gives them the special name "Zobtenite." *Allgem. u. chem. Geol.*, Bd. ii., p. 184.

basic types do not appear freely—firstly, because the composition of such rocks, whether they are sedimentary or igneous in origin, is not suited to the development of large felspars and coarse structures under metamorphic action *combined with movement;* secondly, because any such bolder crystals already existing in a primary basic mass become, from their composition, readily broken down; these recrystallise in granular and microlitic forms, so that the ultimate result of earth-pressure is a fine-grained rock which one would class without hesitation with the schists. To take an extreme case, serpentine-schists abound; but an olivine- or a serpentine-gneiss would seem a structural impossibility.

On the other hand, highly silicated rocks seem more abundant in the outer layers of the earth's crust, and thus account for the large areas of gneiss. The occurrence of basic rocks appears to be more of the nature of an accident, and due to the local protrusion of matter from a lower level, or to the refusion of material already so protruded.

Note.—GRANULITE is a term for a great group of rocks, mostly metamorphic, which have as a common character a fine-grained granular structure. They are of a most varied composition, and must be regarded as structural varieties of a number of well-known rocks. The remarkable "trap-granulites" appear related to the granular diorites and gabbros (p. 230), and their constituents are probably recrystallised products, being clear and beautifully fresh under the microscope. Recent research in Germany tends to show that such rocks arise as products of thermo-metamorphism; and their constituents may be derived partly from altered sediments and partly from the invading igneous rock. Mr. Harker has described similar pyroxene-granulites as resulting from the immersion of basalts in the granite magma of the Isle of Skye ("Igneous Rocks of Skye," *Geol. Survey*, 1904, p. 115). At the opposite extreme are the common quartzose granulites, which are granular quartzites, often with accessory minerals. Some of the Swedish "halleflintas" are metamorphic products; others may be eurites or old lavas.

Many of Haüy's "Leptynites" (a name given because the felspar particles are "thinned down" in their dimensions) are felspathic granulites; but a more precise name can often be assigned to them in the field, when they prove to be granular aplites, or eurites containing mica derived from adjacent schists, or even felspathic sandstones altered by contact-metamorphism.

The common microscopic character of the granulites is the occurrence, as above stated, of a fine-grained granular structure. Foliation may be also visible, but is not necessarily distinct so far as sections are concerned.

PART IV.

THE EXAMINATION OF FOSSILS.

"The search for a fossil may be considered as least as rational as the pursuit of a hare."—WILLIAM SMITH, *Stratigraphical System of Organized Fossils*, 1817.

"Neque mirandum in mediterraneis, et montibus altissimis reperiri animalia maritima in lapides conversa, non enim absurdum est, ubique mare extitisse."—CAESALPINUS, *De Metallicis*, 1596.

CHAPTER XXI.

INTRODUCTORY.

THE exact determination of fossil species is a matter rather for the specialist than for the student or the geologist in the field. The proximity of good libraries and continually revised museum-collections is essential for the comparison of the specimens collected with accurately defined types of species. But every geologist should be acquainted with the principles that guide the palæontologist, and with the points on which he relies for the discrimination of the more important genera of fossil forms.

There are certain names that are household words among geologists, although possibly of little interest in pure zoology. Every reader of text-books encounters *Phacops* and *Productus*, *Trigonia* and *Limnæa*. He collects, moreover, with enthusiasm in the field, where he views, among limestone scarps or delicately bedded shales, a fauna almost in its habit as it lived. In leisure hours he endeavours to connect what he brings home with the types selected by stratigraphers. In the following pages, therefore, we propose to give an outline of the characters of the most typical and abundant fossil genera, confining ourselves to inver-

tebrates and mainly to forms well known in the British Isles. Prefixed to the account of the members of each class is a kind of glossary of the terms ordinarily used in the description of such of their parts as are found fossil. It is hoped that by this means the reality of the distinctions made between the remains of certain genera, and the reality of the relationship between others, may be adequately grasped, and that attention may be called to the features which should obtain prominence in the description of a fossil form.

Such features may or may not possess importance to the zoologist. It must be remembered that we are here examining fossils from a rather limited and geological standpoint, our first consideration being, what is the age of any series of deposits, and secondly, what were the conditions prevailing in the area under examination at the time that any particular bed was being laid down? We have examined the mineral features and have classified the rocks. The age of the deposits is a matter of paramount interest and importance, and the species of fossils are our surest guide. The assemblage of genera will, however, be of very considerable service in the absence of means of accurately defining species; and this assemblage, moreover, will generally answer the question as to the prevalence of fresh-water or marine, shallow-water or deep-water conditions.

Hence, while the philosophic zoologist may be inclined to think lightly of elaborate specific distinctions, the geologist has to consider animals and their remains from a position peculiarly his own. While a zoologist looks vertically down each long chain of life-forms that has yielded us an existing species, the geologist endeavours to look horizontally across all the lines at once, cutting, indeed, the complex structure of chains, continuous or bifurcating, with a plane that comes in contact merely with the contemporaneous links.

Moreover, he has to deal almost entirely with the hard parts of his animals, or with the mere leaves of plants dissociated from reproductive structures. His fossils must be classified largely by conjecture, and often by means of characters, as we have pointed out, of doubtful zoological value.

In this little book we deal purely with the relics known as fossils, not by any means ignoring that most fascinating science, palæontology, but looking merely at one branch of it, which we might term "sclerography," the description of hard parts only. Questions of life-history, animal structure, or relationship with modern forms, we must leave to zoological and palæontological writers; and we need scarcely add that an acquaintance with

such matters is pre-supposed in every serious student of fossil remains. The worker who would, for the purpose of an examination or the labelling of a collection, go through the following pages without looking beyond them, without endeavouring to picture a fossil as part of a living moving fauna, may acquire a number of disconnected facts, but will scarcely be in a position to apply any one of them to the explanation of stratified deposits in the field.

The order in which the classes of organisms are here arranged is purely utilitarian. The Hydrozoa, Actinozoa, and Polyzoa, have thus been treated in succession, owing to the difficulty sometimes experienced in correctly assigning a fossil colonial organism to any one of these divisions. The Lamellibranchiata follow on the Brachiopoda, so that the contrasts between the two groups of bivalve shells may be emphasised. The Echinodermata and the Annelida thus obtain a somewhat late position; but even zoologists will hardly object to the splitting-up of the heterogeneous group of "Vermes."

The genera selected are arranged simply under their respective classes, and occasionally orders, without division into families. The alliance between any two or more forms that may be discussed is, however, pointed out, and a black line between two descriptions marks the passage to a fresh group of types. Such descriptions as are here given cover only a small portion of the ground, and, when a specimen under examination fails to agree in essential features with any of those quoted, its characters should be written down, and comparison made at the first opportunity with examples in museums and with the details in special works, such as the volumes below mentioned or the publications of the Palæontographical Society. Practice in describing fossils will naturally develop greatly the observation of their essential structures.

The division of fossil forms into marine, brackish-water, or fresh-water, is naturally difficult in some cases; and to reason from analogy with modern forms is likely to be misleading. But, from the association of one fossil genus with another, and from the physical characters of the strata in which they lie, we can add information on this important point with confidence in the case of most of the common forms about to be discussed.

Works on Animal Palæontology.

F. Bernard.—Éléments de Paléontologie. Baillière, Paris, 1895. Very well illustrated. See note to Zittel below.

P. FISCHER.—Manuel de Conchyliologie. Savy, Paris, 1887. On the lines of Woodward's work, extended and brought admirably up to date.

HOERNES.—Elemente der Palaeontologie (Palaeozoologie). Veit. Leipzig, 1884. (Also a French edition by Dollo; pub. by Savy, Paris, 1886). A handy one-volume work.

NICHOLSON AND LYDEKKER.—Manual of Palæontology. Blackwood, 1889. 2 vols.

PHILLIPS.—Manual of Geology. (Physical Geology, Stratigraphy, and Palæontology.) Edited by R. ETHERIDGE and H. G. SEELEY. C. Griffin & Co., London. 2 vols.

QUENSTEDT.—Handbuch der Petrefaktenkunde. Laupp, Tübingen, 1885. 2 vols.

STEINMANN.—Elemente der Paläontologie. Engelmann, Leipzig, 1888-1890. (Especially clear figures.)

H. WOODS.—Elementary Palæontology; invertebrate. Cambridge Univ. Press. 3rd ed., 1902.

S. P. WOODWARD.—Manual of the Mollusca. 1st edit. pub. by Weale, 1851-6. Now pub. by Crosby, Lockwood & Co. Includes modern forms, and is in many respects a classic.

A. SMITH WOODWARD.—Outlines of Vertebrate Palæontology. Cambridge Univ. Press, 1898.

ZITTEL.—(i.) Handbuch der Palaeontologie. Oldenbourg, Leipzig, 1876 and onwards. (French edition by Barrois; pub. by Doin, Paris.) 4 vols.

(ii.) Grundzüge der Palaeontologie (Palaeozoologie). 2nd ed., 1903-5. This involves many revisions of points in the previous "Handbuch," and like the work of Bernard, forms one of the most comprehensive works extant. A considerably modified English version by C. R. Eastman and others is published by Macmillan (3 vols., 1900, &c.).

MODE OF OCCURRENCE AND PRESERVATION OF FOSSILS.

Some rocks, from their mineral and physical constitution, are admirable preservers of fossils, while others contain few or, perhaps, none. In this latter case diligent search must be made for casts and impressions, and concretions of ironstone, silica, &c., must be examined for their included and protected fossils. Even if there are no fossils, it may still be possible to correlate the strata with others in which fossils are abundant.

Thus sandstones are often devoid of fossils for various reasons. Apart from their permeability, the coarser grits and the conglomerates would be likely only to contain fragments, since the materials would grind delicate shells to pieces during the actual deposition of the rock.

Clays preserve shells excellently, but extraction when the rock is moist is almost hopeless. The dried talus at the foot of a clay-exposure, or the small rubbly lumps thrown aside in a brick-pit and broken up by sun-cracks, may be turned over with great

advantage. Now and then slabs or lumps can be cut out and allowed to dry slowly on a shelf at home. (See p. 198.)

The concretions of calcareous or phosphatic matter, or of clay-ironstone, in clays must be broken open in the search for fossils, since they split fairly along the planes of bedding and often reveal shells in excellent condition.

In clays the fossils are often pyritised, the material being commonly marcasite, the decomposable form. Casts, true pseudomorphs, and nodular concretionary aggregations surrounding fossils, occur in this material. The cubic iron pyrites (pyrite) is stable; but the less lustrous marcasite goes to pieces gradually, and specimens become reduced in the cabinet to an efflorescent powdery mass. Coating the fossil with varnish, or boiling in paraffin, will retard, if it will not entirely stop, this very deleterious process.

Limestones are a fruitful source of fossils, since they so commonly originate in the accumulation of organic remains. But the extraction of individual specimens is often difficult enough. We have mentioned this matter and the cleaning of fossils when dealing with the limestones as rocks. Suitable specimens will often occur weathered out in the water-ways of the rock, whether joint-surfaces or conspicuous planes of bedding. In compact limestones the edges of the fossil shells are again and again seen, but recognisable forms are only to be obtained by turning over blocks that have been long exposed upon the talus, or by splitting mass after mass until a fortunate fracture occurs which passes round and not through some resisting fossil.

In dolomites the shells, corals, &c., are often lost by solution and recrystallisation during the mineral changes in the mass.

In all limestones fossils are liable to be preserved as casts in flint, or other varieties of chalcedony. The shell itself breaks away on disintegration of the rock, and the siliceous casts are found as "derived fossils" in gravels of far later date, as on the Surrey Downs.

Pseudomorphs or casts in carbonate of iron, hæmatite, &c., may be expected.

Under the head of Shelly Limestone reference has been made to the work done in the determination of the constitution of shells—*i.e.*, whether they consist of calcite or aragonite (p. 201). Some, as Lingula, contain a great proportion of phosphate of lime.

We have also mentioned various modes of extraction of small fossils from clays, &c.* Such isolated specimens may be mounted

* For "Modern Methods in the Study of Fossils," see A. S. Woodward, *Proc. Geol. Assoc.*, vol. xix. (1905), p. 69.

like sand-grains, either as opaque or transparent objects. Many collectors mount larger fossils with fish-glue or other cement, upon wooden tablets, the label being affixed below; but both surfaces of the shell should be represented, and for all collections a loose specimen in a card tray * is probably best. The specimen should have a number upon it, corresponding to that on the label in the tray. Small forms can be conveniently kept in little glass specimen-tubes with corks, which are to be obtained of any dealer in natural history objects; they can thus be inspected easily from all points of view without actual handling. A label-slip can be written and placed within the tube itself.

Collections, of course, vary greatly according to the district which it is most important to represent. In our concluding pages we give a suggested list of typical fossils from the principal divisions of the strata of the British Isles, with a few foreign additions to render the series more continuous from the point of view of geological time. It is very easy to improve upon this list by the addition of further forms; but we trust that as a basis, and as the nucleus of a collection, it will be found to be fairly representative. Some of the forms, such as Olenellus, though very characteristic when found, are too rare to have a a place in ordinary collections.

Lastly, in procuring characteristic fossils, we must carefully note in the field the distinction between the remains of animals that were contemporaneous with the deposition of the strata and those which have been washed in as **derived fossils** from earlier formations. The effects of rolling and rounding on the latter can generally be detected, and such fossils have often, moreover, undergone considerable mineral change. They may also be found to be filled with material differing from that by which they are now surrounded—a very useful and interesting observation.

* Such trays cost about 5s. to 10s. a gross, according to size. Mr. A. Kent, 11 Nassau Street, Shaftesbury Avenue, London, is a well-known maker.

TABLE OF THE TERMS USED IN REFERRING TO THE GEOLOGICAL FORMATIONS.

CAINOZOIC.	POST-PLIOCENE and RECENT (including the present time).	
	PLIOCENE.	
	MIOCENE.	
	OLIGOCENE.	
	EOCENE.	
MESOZOIC.	UPPER CRETACEOUS	(*Lower*, *Middle*, and *Upper Chalk* in Britain).
	LOWER CRETACEOUS	(*Wealden* to *Gault* and *U. Greensand* in Britain).
	JURASSIC.	UPPER (*Oxford Clay* to *Purbeck*; with *Tithonian*).
		MIDDLE (*Midford Sands* to *Cornbrash*).
		LOWER (*Lias*).
	TRIAS (including *Rhætic*).	
PALÆOZOIC.	PERMIAN.	
	CARBONIFEROUS.	
	DEVONIAN.	
	GOTLANDIAN* (*Llandovery* to *Ludlow Series* in Britain).	
	ORDOVICIAN (*Arenig* to *Bala Series* in Britain).	
	CAMBRIAN (*Taconian* to *Tremadoc Series* in Britain).	

Note.—**Range of Genera.**—It must be borne in mind that the range of a genus in time, as stated in text-books, must always be liable to extension through new discoveries. Hence it is of more importance to realise the time and conditions of maximum development of a genus than to define its exact horizons of appearance and disappearance, which, indeed, can never be more than approximately known.

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* This term was proposed by De Lapparent ("Traité de Géologie," 3me. éd., 1893, p. 748) for the "Upper Silurian," as a parallel with Lapworth's "Ordovician" for the "Lower Silurian" strata.

CHAPTER XXII.

FOSSIL GENERIC TYPES.

I. Rhizopoda.

A. Foraminifera.

Modern forms of the shells of these protozoans may almost invariably be sifted out, or selected by the eye, from the finer material of our beaches. While some are built up of agglutinated sand-grains, spicules, &c. ("Arenaceous" types), the majority met with are calcareous. The latter fall into two divisions, the "Imperforate" types and the "Perforate," so named from the absence or presence of minute perforations in the shell.

Under the microscope, the calcareous shells, when isolated, are not so perfectly transparent as the siliceous shells of the Radiolaria; in the perforate forms the minute tubules of the walls give fragments a fibrous effect when viewed sideways, and a pitted effect when looked at from the outside or inside of the shell. With crossed nicols these calcareous shells show the dark cross due to the fibrous aggregate structure (p. 149), and their anisotropic character is a ready means of distinguishing them from the istropic siliceous skeletons of radiolaria, sponges, or diatoms.

Glauconite is frequently found in association with these shells, partially or completely filling the chambers with a darkish green deposit. Casts are thus formed of the interior, and may remain in rocks after the complete removal of the shell.

Some practice will be required in picking out foraminifera from among other small shells, such as young gastropods and bivalves, which may only distantly suggest the corresponding adult forms. In sections, the chambered character of all typical foraminifera is sure to be successfully revealed. The mode of making sections of isolated forms is described on p. 129.

For a correct appreciation of the characters and variety of type of this important rock-building group, we may refer to the plates illustrating Mr. Brady's magnificent "Challenger" Report.

(a.) *Imperforate Calcareous Shells.*

Shells probably formed of aragonite, and resembling white porcelain (whence the group-name "Porcellanea"); without perforations in the external wall, excepting at the terminal "mouth" or along the outer face of the last series of chambers in some coiled forms (as along the margin of Orbitolites). Marine; generally shallow water.

Miliola (or "Miliolites").—Formed of pillow-shaped chambers which succeed one another in a spiral, the plane of which is in some varieties shifted during growth. The chambers lap round and conceal the preceding ones partially or entirely, and many subgenera have been established on variations in this character. Sections are, however, very characteristic. *Trias* to *Recent;* particularly *Cainozoic.*

(b.) *Perforate Calcareous Shells.*

Calcite shell, transparent and glassy-looking ("Vitrea") in modern examples, with abundant perforations over all the surface. The filling-up of these pores gives fossil examples a duller appearance. Long delicate spines project from the surface of some genera, but are very rarely seen, even as stumps, in preparations. Marine; shells found at 2,500 fathoms at present day, but they often sink from surface.

Lagena.—A single chamber shaped like a Florence-oil flask, with or without an elongated neck. Surface smooth or ribbed. *Gotlandian* to *Recent.*

Nodosaria.—A series of Lagena-like chambers succeeding and partially overlapping one another in a straight line (a curved variety is called Dentalina). The last and largest chamber shows a terminal mouth, corresponding to the neck in Lagena. *Carboniferous,* but mostly later and *Recent.*

Textularia.—Chambers in two series, united along one side, those on one hand alternating with those on the other. Viewed sideways, this gives the effect of plaited work, the chambers being elongated in an outward direction. Arenaceous forms with similar structure are common. Particularly *Cretaceous.* Closely allied forms abundant in *Carboniferous.* Also *Recent.*

Globigerina.—Chambers spheroidal, agglomerated on one another and partially overlapping, often with a trace of spiral arrangement, the largest and latest chamber having a slit-like mouth. A very common pelagic form. *Trias* to *Recent;* particularly *Cretaceous* and *Cainozoic.*

Rotalia.—Chambers succeeding one another in a spiral, all the coils of which are visible on the upper surface. In sections the septa between the chambers are seen to be double, and there is a very interesting approach to the canal-system of the walls of the Nummulinidæ. *Jurassic* to *Recent;* abundant in *Cretaceous* and onwards.

Nummulites (fig. 46).—Chambers arranged spirally and entirely

Fig. 46.—*Nummulites lævigatus* (Bracklesham Beds). (1) Viewed from above; (2) vertical section; and (3) horizontal sections, embedded in the rock.

embracing the earlier coils, thus imitating some types of ammonite. The whole form consequently becomes lenticular, and the great number of the chambers is only realised on fracture. The shell breaks easily across, in the rock or when isolated, and shows on its circular sections a close spiral with numerous curved septa, and on its cross-sections the extended saddle-like shape of the chambers, their investing prolongations being crossed by little bars. The shell often measures 2 or 3 cm. in diameter, and sometimes as much as 6 cm. The surface is typically smooth, sometimes showing wavy linear markings. An undulated folded appearance is characteristic of the larger specimens. The great size of this foraminifer and its abundance on certain horizons make it an important rock-constituent.

In a sub-genus **Assilina** the coils do not overlap, so that the spiral form is visible at the surface.

In section the septa are seen to be double, and the "intermediate skeleton" with its canal-system is well developed, the walls being greatly thickened by it.

Carboniferous to *Recent.* Very abundant in the *Eocene* ("Nummulitic strata"). Small forms still living.

Orbitoides.—In form, size, and outer appearance much like Nummulites, but shows when broken across a great number of small chambers lying in layers above and below a median band of more regular and larger ones. In sections parallel to the

layers, the chambers of the median layer are seen to be divided from one another by straight septa, which alternate in position in the successive coils of the shell. Canal-system well developed between the chambers and in the septa.

U. Cretaceous to *Miocene*. Very abundant in *Eocene*.

Fusulina.—Spindle-shaped, some 10 mm. long. The coiling takes place spirally round an axis. The somewhat irregular septa are not double, and there is no canal-system.

Carboniferous and *Permian*.

(c.) *Shells Formed by Agglutination.*

A number of these, built up of sand grains and other particles, occur in the Carboniferous Limestone and thenceforward. (See Textularia, p. 295).

Saccammina.—Shell like Lagena, but with two short necks at opposite ends; sometimes these necks serve to connect adjacent shells, and a form like Nodosaria arises. On weathered surfaces of limestone the cells stand out like little globes some 3 mm. in diameter. When broken or in section, the wall is seen to be thick and arenaceous.

Carboniferous. Also known in *Recent*.

Endothyra.—Allied to Rotalia, but the shell is largely built up by agglutination of calcareous grains. Mouth simple, on inner margin of last chamber.

Carboniferous.

B. Radiolaria.

The remains of these are rarely found fossil (see p. 211), though they have been claimed as occurring even in the oldest rocks.* The skeleton is siliceous, and is colourless, transparent, and isotropic under the microscope. Globular and helmet-shaped forms are common, though a few are discoidal. Forms with one globe within another are very typical. The perforations are bolder than those of the foraminifera, and fragments thus resemble a network; fairly coarse spines and rod-like prolongations are common. A few of the skeletons consist of disconnected spicules. One of the best known fossil deposits of radiolarians is the Miocene "earth" of Barbados, which is a favourite object with microscopic dealers, and in which the characters of the skeletons can be admirably studied.

* See David, *Proc. Linn. Soc. N. S. W.*, 1896, pp. 553 and 571; Hinde, *Ann. and Mag. Nat. Hist.*, July, 1890, and *Quart. Journ. Geol. Soc.*, vol. xlix. (1893), p. 215, pl. iv. For Cretaceous forms, and a discussion of the solution of Radiolarian skeletons, see Hill and Jukes-Browne, *ibid.*, vol. li. (1895), p. 600.

Some few of the radiolaria are flattened or discoidal; but they cannot be confused with diatoms, owing to the far more delicate markings of the latter. Radiolaria should always be looked for in sections of flint (chert).

The radiolaria are marine.

II. Spongiæ (Porifera).

We deal here only with those sponges that possessed a calcareous or siliceous skeleton. They are frequently represented (as has been described on p. 211) merely by isolated spicules, or by casts of these remaining in the flinty layers of the rock.

The principal terms used in describing fossil sponges are:—

Principal Cavity or *Cloaca*.—The large central cavity, such as the hollow in cup-shaped forms.

Osculum.—The exhalent aperture constituting the mouth of this cavity. See Ostia below.

Canals.—Tubes traversing the skeletal mesh.

Ostia.—The terminal openings of the canals, placed commonly in the wall of the large cavity. Often also called Oscula.

Pores.—Smaller inhalent openings in the surface of the mesh, connected with the canals when these are present.

Spicules.—The bodies that build up the main mesh-work.

Dermal Spicules.—Small bodies of various form, even globular, found mostly in the outer layers of the sponge.

The sponges here treated of are marine.

A. Siliceous Sponges.

The isolated spicules (fig. 47) are typically rod-like, with an axial canal, so that fragments under the microscope, being clear and colourless, resemble pieces of minute thermometer-tubes. These rods may bifurcate, may meet in solid or delicately hollowed nodes, and may acquire, in different parts of the same sponge, a great variety of form. The dermal spicules are often widely different from those constituting the main mass of the skeleton.

The siliceous spicules are soluble in hot caustic potash solutions. In nature, moreover, they are frequently represented by pseudomorphs, whether in iron pyrites or limonite, as occurs in our Cretaceous beds, or calcite, as in some Jurassic strata of South Germany. Hence, while some most delicate specimens can be extracted from their calcareous matrix by treatment with

dilute acid, others will dissolve away in a manner most disappointing to the collector, however full of interest the experience may be from a mineral point of view.

Fig. 47.—Sand containing abundant Spicules of Siliceous Sponges. Hythe Beds, Tilburstow Hill, Surrey. × 40. *g*, Dark and almost opaque granules of glauconite. *h*, Hexactinellid spicules. *l*, Lithistid spicules, a large one occurring near the centre of the field. *s*, Grains of angular quartz sand. *t*, Tetractinellid spicules of various types. The detached rods belong also, in all probability, to tetractinellid forms. In all these spicules the canal is liable to become rather prominent, through its enlargement by solution and subsequent infilling with glauconite or fine clay.

Order 1. MONACTINELLIDÆ.

Spicules consisting of a single ray, pointed at both ends.

Cliona.—Though the spicules are not known in the fossil species, the borings of this sponge are found, commonly as casts formed by silica. These casts are like little flattened nodules, about 3 mm. in diameter, connected by threads, also of flint; they represent the chambers excavated by the sponge and the delicate passages ("stolons") which led from one to another. The shell-substance in which the borings were made has in such cases been removed after the infiltration of the silica.

Gotlandian (?) to *Recent*.

Order 2. Tetractinellidæ.

The typical spicules consist of four rays, three of which branch out, making equal angles, from the end of the fourth and much longer ray. Dr. Hinde states that the spicules occurring in the flints and cherts "in the Oolite, the Lower and Upper Green Sand, and the Upper Chalk are principally of Tetractinellid sponges,"* the remains of which are not satisfactory enough for generic determination (fig. 47).

Order 3. Lithistidæ.

Typical spicules irregularly branching, and set with little knotty outgrowths; often closely interlacing at the ends. A four-radial type is occasionally set up, especially among the dermal spicules, some of which may, however, be monoaxial.

Doryderma.—Cylindrical, often branching, with numerous vertical canals running up the main body and the branches. These are often infilled by flint and much obscured.

Typically *Cretaceous* (*Albian* to *Senonian*). Known in *Carboniferous.*

Siphonia.—Commonly pear-shaped or like the bud of a tulip, with a short or long stalk, which has, when perfect, rootlets at the end. Principal cavity reaching from apex to about centre of sponge (often filled with silica), with the ostia of canals opening into it. Canals forming a curved series running roughly parallel to the surface of the sponge and down into the stalk; a second series of smaller tubes crosses these obliquely down from the exterior to the interior of the sponge. When viewed from above, canals are commonly seen radiating from the edge of the great osculum.

Cretaceous; particularly *Upper Greensand* to *Senonian.*

Hallirhoa.—Like Siphonia, but divided into lobes by depressions of the surface, which radiate from the stalk and even run vertically up the whole body of the sponge.

Cretaceous (*U. Greensand*).

Order 4. Hexactinellidæ.

Spicules with six rays, meeting at right angles in a "node;" these spicules are often united by their ends so as to form a

* *Catalogue of Fossil Sponges. British Museum,* 1883 (with plates), p. 28.

structure of beautiful regularity, resembling that produced by the crossing poles of a scaffold. Dermal spicules of various form.

Ventriculites.—Cup-shaped, narrowed or expanded, not branching, with rootlets at base. Wall delicately folded, the axes of the folds running from the margin of the cup to the base, and the folds being almost in contact with one another. Principal cavity very deep, with ostia of radial canals opening on it in vertical rows. These canals do not reach the outer surface; others open similarly on the outer surface, but do not reach the principal cavity. The vertical rows of ostia are sometimes represented by furrows. Spicular mesh fairly regular, and easily seen in sections; often replaced in Chalk specimens by limonite, derived from marcasite. The base of the sponge is, moreover, often surrounded and infilled by compact flint, while the upper part of the cup has been dissolved away or is represented by a mere impression or a ferruginous stain.

U. Cretaceous.

Plocoscyphia.—An irregular mass formed, as it were, by the crumpling and rolling together of a sheet-like hexactinellid wall, so that a number of roughly circular or greatly elongated apertures are left, each of which may represent an osculum. The walls of the irregular tubes thus formed sometimes show ostia, and are constructed of a regular hexactinellid mesh. Replaced by iron pyrites at times.

Cretaceous (particularly *Cenomanian* and *Turonian*).

Note.—The earlier Palæozoic sponges have some relation to the Hexactinellidæ, but are represented by a surface-web only. The spicules in this are plain rectangular crosses, with smaller ones set in each square formed by the union of their arms, and yet smaller crosses in the subordinate squares thus produced. The arms of all these cross-shaped spicules lie parallel and perpendicular to those of the primary cross, until detached by fracture of the layer. A type is the *Cambrian* **Protospongia**, the spicules being sometimes pyritised, sometimes mere impressions in the shales.

B. Calcareous Sponges.

The fossil types come under the family of the Pharetrones, in which there is a thick wall, with a dermal layer rarely well preserved. The calcareous spicules are mostly formed of three rays meeting at 120°, or at times of four rays and even one ray. By almost complete suppression of one ray, some three rayed spicules appear monoaxial. The spicules are commonly grouped in fibrous bundles. (See Sollas, *Journ. R. Geol. Soc. Ireland*, vol. vii., p. 37.)

The ready decomposition of the spicules makes the form of the sponge more relied on in this division than is the case in the siliceous sponges. The substance of the wall may, indeed, during fossilisation become merely an irregular calcareous tissue.

Peronidella (**Peronella**). — Tubular, cylindrical, sometimes branching. Principal cavity extends to base; round osculum at summit. No canal-system in the thick wall.

Devonian to *Cretaceous*; especially abundant in *Jurassic* and *Cretaceous*.

Tremacystia.—Form much like Peronidella; sometimes club-shaped. The tubular cavity is crossed by dome-like or flatter partitions, the chambers thus formed communicating by a hole in the centre of the partition, or by holes in the sides of a tube, which runs from one partition to the other parallel to the axis of the sponge. Minute canals in the wall.

The characteristic internal structure is easily seen in broken specimens. This genus (Hinde) includes Steinmann's **Barroisia**.

Cretaceous; mostly *Lower Cretaceous*.

Rhaphidonema.—Cup-shaped, expanded or narrower. A compact dermal layer extends over either the outer or inner surface; this is pierced by ostia in all species but *R. farringdonense*. Canals traverse the wall approximately perpendicular to the surface.

Cretaceous.

III. Hydrozoa.

The body formed by the aggregate-growth of these colonial organisms is styled the *Hydrosome*. Where the hydroid polype possesses a cup-like cell, this is styled the *Hydrotheca*.

A. Forms with a Massive Calcareous Base from which the Polypes protruded during Life.

Stromatopora.—The base is built up of mammillated layers which, with the columnar structures that connect them, form an irregularly reticulated structure. In section little tubes with horizontal partitions are also seen in the mass, and in these the polypes are believed to have lived. The mass is often 15 or 20 cm. across, and is roughly hemispherical, the surface showing small mound-like elevations.

Gotlandian and ***Devonian***.

Labechia.—The base is rather compact to the eye, and its under side is smooth, with some concentric wrinkles. The upper

surface is set with numerous tubercles, which are not perforated, and which are the ends of columns rising from below. In vertical sections a cellular irregular calcareous tissue fills the interspaces between these columns. The polypes are believed to have lived merely on the surface of the calcareous and often encrusting base which we now find.

Ordovician and *Gotlandian;* some in *Devonian.*

B. Graptolites.

The hydrothecæ are arranged along an external flexible chitinous axis, and their cavities are connected internally. The solid axis (*Virgula*) is often prolonged without bearing hydrothecæ. At one end of the axis in perfect specimens is a triangular body, the *sicula,* from which the hydrosome arises. The hydrothecæ nearest the sicula are the smallest, and are sometimes absent about this point of the hydrosome. The chitinous hydrosomes are commonly flattened into mere films upon the surfaces of shales. The Graptolites are *Cambrian, Ordovician,* and *Gotlandian,* the branched forms, and those with two rows of hydrothecæ on one axis, being the earlier. At present, investigators of graptolites are likely to pay less attention to the form of the hydrosome than to the modifications of the hydrothecæ (see Nicholson and Marr, "Phylogeny of the Graptolites," *Geol. Mag.*, 1895, p. 529). For recent views on their mode of life and flotation, see Roemer and Frech, "Lethæa geognostica," Bd. i.; Lf. 3 (1897), p. 552

The graptolites are marine.

Diplograptus.—Hydrothecæ forming two rows, on opposite sides of a common axis. The hydrothecæ are set obliquely and in contact laterally. *Ordovician* and *L. Gotlandian.*

Climacograptus.—Similar, but hydrothecæ set at right angles to axis and separated laterally. *Ordovician* and *L. Gotlandian.*

Monograptus.—Hydrothecæ forming one row and in contact. Hydrosome commonly straight; sometimes coiled spirally, in one plane or like a screw. *Gotlandian.*

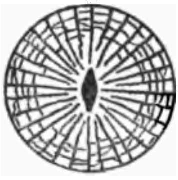
Rastrites.—Hydrothecæ forming one row on the convex side of a thin spiral axis, and distinctly separated laterally from one another. *L. Gotlandian.*

Didymograptus.—Hydrosome formed of two equal branches united by the sicula; hydrothecæ in a single row on each branch and in contact laterally. The branches are sometimes spread widely apart; sometimes they form a V, and the openings of the hydrothecæ on one row thus almost face those on the other. *Ordovician.*

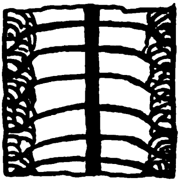
Note.—In **Dictyonema** the hydrosome is composed of a great number of radiating branches connected by little cross-rods so as to form a net-work. These branches in reality consist of hydrothecæ arranged in linear series, with their apertures at the upper ends. No common axis occurs (Roemer, *op. cit.*, p. 570). *Cambrian* to *Devonian.*

IV. Actinozoa.

The forms here mentioned belong entirely to the corals which possess calcareous skeletons. The material is in most modern types aragonite; but Mr. Sorby believes that in the Palæozoic forms it was originally calcite, as now found. All are marine.



a



b

Fig. 48.—Diagrams of *Lithostrotion*. *a*, View of the calyx from above; a flattened columella is in the centre; the septa form two series, and the edges of upturned dissepiments are also seen. *b*, Vertical section passing through the columella. Several tabulæ, convex upwards, are seen; and numerous dissepiments appear, forming a vesicular mesh which extends for some way inwards from the wall.

While the older division of corals into Octocoralla, Tetracoralla, and Hexacoralla, seems likely to be abandoned, we cannot yet regard any later system of classification as approaching finality. The general structures embodied in the "Tetracoralla" represent an early type, though their frequent bilateral symmetry may have been based upon a still earlier six-rayed type. At present, the division into Alcyonaria and Madreporaria is all that will be here attempted.

Terms used:—

Theca.—The bounding wall of the cup occupied by the individual coral-polype; often only feebly developed.

Epitheca.—A smooth external covering to the theca, or to the base and sides of a compound corallum.

Costæ.—Vertical ridges projecting from the outside of the theca and forming ribs which generally correspond to the septa. When, as in many older corals, they alternate with the septa, they have been called "Rugæ."

Calyx.—The cup-like depression in the upper part of the skeleton, occupied by the alimentary cavity during life.

Fossula.—A groove-like pit in the floor of the calyx of some corals (see p. 306 and fig. 50).

Septa.—Vertical partitions arising from the inner surface of the theca, and converging towards the centre of the cup. Each septum underlies a tentacle of the living animal, and they thus alternate with the soft partitions or mesenteries. They sometimes are produced outward into costæ. The septa occur in "cycles;" a primary series, a second and commonly shorter series intercalated between these, a third in the interspaces thus formed, and so on (fig. 50).

Columella.—A rod-like or vesicular axis arising in the centre of the cup.

False Columella.—A similar axis formed by the union and intertwisting of the edges of the septa where they meet in the middle line of the cavity.

Pali.—Vertical partitions that sometimes arise in the central area, between the columella and the edges of the septa; they are sometimes joined to the columella.

Tabulæ.—Horizontal or curved partitions that successively cut off the lower part of the cup, thus forming a new floor (fig. 48, *b*).

Dissepiments.—These are often regarded as imperfect tabulæ, and are little plate-like connexions running in curves or fairly horizontally between adjacent septa, and producing a vesicular structure in the interspaces.

Synapticulæ.—Similar to dissepiments, but rod-like or tubercular.

Corallite.—A name sometimes given to the skeleton of an individual in a compound coral.

Corallum.—The whole skeletal mass formed by a colony or "compound coral."

Cœnenchyma.—The "exothecal" material connecting the corallites in some compound corals, and thus common to all the individuals.

Astræan Mode of Growth.—The lateral buds of the dividing individuals have grown up side by side and in contact, so as to produce a compound structure of more or less polygonal forms (fig. 52).

Simple coral.—The individual is isolated. It does not divide by branching.

A. Alcyonaria (Octocoralla).

The septa, when present, are not related to the eight tentacles of the animal. Hard parts calcite.

Heliolites (fig. 49).—Corallum often rudely spheroidal; sometimes extended or branching. Calyxes widely divided by what appears to be cœnenchyma, and furnished with septa (almost always 12), which are sometimes short and sometimes meet in the centre. The cœnenchyma is set with abundant smaller openings, regarded by Nicholson as having contained rudimentary polypes ("siphonozooids"). In section both the larger and smaller sets of tubes show distinct tabulæ.

Gotlandian and *Devonian*.

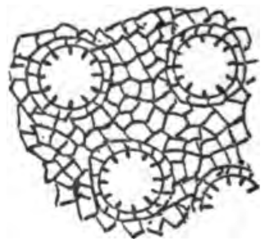


Fig. 49.—*Heliolites interstinctus* (Wenlock Beds). Viewed from above and enlarged; showing the 12 septa and the cellular character of the areas between the calyxes.

Note.—Several of the genera placed in Group C may with probability be referred to the Alcyonaria.

B. Madreporaria.

In many of the older types of corals there may be six primary septa in early stages, though four appear higher in the corallite.* One of these latter, the "principal" or "cardinal" septum, and the one opposite to it divide the calyx into two symmetrical halves, the septa on either side of the principal one, and between it and the two "lateral" septa, being, in well marked types, directed towards the principal septum rather than towards the centre of the coral; they are thus said to be "pinnate" upon that septum (fig. 50). Between one lateral septum and the other over the remaining area the septa point towards the centre. Hence the arrangement is, as a whole, bilateral rather than radial.

The primary septa are sometimes large, sometimes much reduced in size; the principal one may lie in a fossula, which is, indeed, formed by local diminution of the septa. In many forms, however, it is impossible to mark out the primary septa from the others; in such cases the symmetry appears truly radial (fig. 48, *a*).

Tabulæ are almost always present in the older types, and

* See Duerden, *Ann. Mag. Nat. Hist.*, ser. 7, vol. ix. (1902), p. 381.

cœnenchyma is commonly not developed, the compound forms being branching or astræan. In other types, which greatly preponderate in later periods, there are six primary septa, and radial symmetry prevails in adult forms. Tabulæ are practically absent.

Zaphrentis (fig. 50).—Simple; form commonly a curved cone,

Fig. 50.—Calyx of *Zaphrentis*, viewed from above, showing the fossula and two cycles of septa, which have in part a pinnate arrangement.

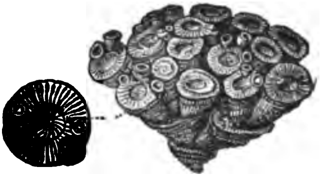


Fig. 51.—*Cyathophyllum truncatum* (Wenlock Beds). Showing budding of new individuals from the calyx.

with epitheca. Abundant septa, the principal one being in a well-marked fossula. Tabulæ run completely across from side to side of the section formed by breaking open or cutting the coral. No columella. **Caninia** is an ally with vesicular outer wall.

Gotlandian to *Carboniferous;* abundant in latter.

Cyathophyllum (fig. 51).—Simple, branching, dendriform, or astræan, with epitheca. Abundant septa, which reach to the centre, and are there sometimes twisted against one another, as may be seen on polished sections. A vesicular calcareous tissue is formed nearest the theca, and the tabulæ often extend across the central part of the cavity.

Ordovician to *Carboniferous;* abundant in *Gotlandian* and *Devonian.*

Lithostrotion (fig. 52).—Dendriform or astræan. In other structures like Cyathophyllum, but distinguished by presence of a well-marked columella, which is spindle-shaped in horizontal section. The longer septa are sometimes united to the columella.

Carboniferous.

Lonsdaleia.—Like Lithostrotion, but divided by an inner wall into two portions—a cellular part next the theca, and an inner more clearly septate portion. Columella large, elliptical in section, and built up of irregular concentric layers.

Carboniferous.

Omphyma (fig. 53).—Simple, the cup-form often rather expanded, with root-like processes of the theca near the base.

Numerous radial septa, four primary ones being seen, in well preserved specimens, to be set in shallow fossulæ. Tabulæ and tissue as in Cyathophyllum.

Gotlandian.

Fig. 52.—*Lithostrotion basaltiforme* (Carboniferous). Astræan growth.

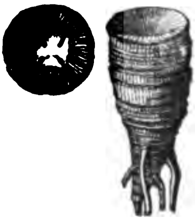


Fig. 53.—*Omphyma turbinatum* (Wenlock Beds). Showing rootlets, and the fossulæ as seen from above.

Calceola (fig. 54).—Simple; shape like the pointed toe of a slipper, the calyx reaching to the base of the coral. Epitheca, ribbed on the flatter side of the cup. Septa reduced to mere little bars. A lid, the *Operculum*, fits on the top of the calyx, though often lost in ordinary specimens. This lid resembles outwardly, with its curvilinear markings, the dorsal valve of many brachiopods, and Calceola was, indeed, long considered as a brachiopod.

Fig. 54. — *Calceola sandalina* (Devonian). Operculum removed.

Devonian.

Litharæa.—Compound, with small, if any, areas of cœnenchyma; the hard parts are formed of a spongy non-compact calcareous tissue. Walls of the corallites pierced by apertures. Septa commonly forming three cycles only, and set with little processes on the edge and on the sides. Columella present, of spongy texture.

Eocene to *Miocene.*

Isastræa.—A typical astræan corallum, without cœnenchyma. Corallites polygonal in section and united by whole length of their walls. Hard parts compact, not spongy. Septa well

marked. Numerous dissepiments. Columella often present, but not strongly developed.

Mesozoic; especially Jurassic.

Montlivaltia.—Simple; sometimes disc-like, with a flat base covered with a concentrically wrinkled epitheca; commonly shaped like a peg-top or a curved cone, also with epitheca. Hard parts compact. Numerous septa, in 12 or more cycles, notched on the edges. Dissepiments abundant. No columella.

Trias to *Recent; especially Jurassic.*

Thecosmilia.—Branching corallum. Corallites often compressed laterally at the calyx and dividing into two; hence two adjacent calyxes often remain confluent. Epitheca present. Hard parts compact. Septa numerous, granulated at sides. Dissepiments abundant. No columella.

Trias to *Miocene; especially Jurassic.*

Thamnastræa.—Compound; corallum commonly like a segment of a sphere supported by an inverted cone, which bears an epitheca. No cœnenchyma, and thecæ unseen, the septa of each corallite running out over the wall and uniting with those of adjacent corallites. Septa fairly numerous and granulated, *i.e.*, set with synapticulæ. Calyx shallow. Columella present.

Trias to *Oligocene.*

Cyclolites.—Simple. Theca forming a flat base, with concentrically wrinkled epitheca. The septa rise above this, forming a fair-sized roughly hemispherical skeleton. Septa thin and very numerous, notched on margin, set with synapticulæ, and pierced by regularly arranged pores. The small septa are generally cemented to the larger.

Typically *Cretaceous.*

Holocystis.—Astræan; corallites united by their costæ and polygonal. Septa not very numerous; four, at right angles to one another, are well marked and larger than the rest. Tabulæ are also present. This genus presents exceptional features, as compared with the more modern types with which it is associated.

Lower Cretaceous.

C. Genera of Doubtful Affinities.

The following genera of Actinozoa are of uncertain position, while Alveolites and Cœnites, from their external aspect, have even been referred to the Polyzoa.

Michelinia.*—Corallum astræan and generally top-shaped, with

* In Nicholson's *Manual of Palæontology*, 3rd edit., vol. i., p. 316, there is an interesting discussion of the relations of this genus and *Pleurodictyum.*

epitheca and rootlets running from it. Corallites united by their walls, which are perforated. Calyx fairly deep. Septa represented merely by striæ, so that the empty polygonal calyxes give the appearance of a honeycomb. Tabulæ and vesicular dissepimental tissue present.

Carboniferous.

Favosites.—Compound; astræan or branching. Corallites resemble polygonal columns when the more massive specimens are broken open. The thecæ show well-marked but widely set perforations. Septa represented by mere striæ. Tabulæ regular and well displayed.

Ordovician to *Carboniferous.*

Alveolites.—Corallum spreading or branching, often of polyzoan type. Aperture of the calyx small, and like a triangle with curved sides; the corallites lie pressed together, somewhat oblique to the surface. Thecæ perforated. Septa represented by one or sometimes three ridges projecting into the cavity. Tabulate.

Gotlandian and *Devonian.*

Cœnites.—Closely allied to Alveolites, but with a thickening of the thecæ near the outer end, so that the mouth of the calyx becomes a mere curved slit, much like the conventional flying bird drawn in landscapes.

Gotlandian and *Devonian.*

Halysites (fig. 55).—Possibly an alcyonarian. Corallites tubular, elliptical in cross-section, and united by their sides in wall-like rows, so as to resemble the pipes of an organ; these bands, each merely one corallite in width, cross one another, leaving large irregular interspaces in the corallum. When infilled with foreign matter, as in ordinary limestones, and broken across, the structure looks like a network of chains, each corallite being a link. Septa rarely traceable. Tabulæ well developed.

Fig. 55.—*Halysites catenularia* (Ordovician).

Ordovician and *Gotlandian.*

Syringopora.—Alcyonarian in type. Corallites tubular, circular in cross-section, bent and ramifying, united only by smaller horizontal tubes. The thecæ thus stand well apart from one another. Septa scarcely traceable. Tabulæ convex downwards.

Gotlandian to *Carboniferous.*

CHAPTER XXIII.

FOSSIL GENERIC TYPES.

V. Polyzoa (Bryozoa).

THESE minute colonial organisms leave skeletons which may be found among the washings of clays and sands, but which may otherwise be often overlooked. Many of the colonies, however, attain to a considerable size.

The hard parts are built up of an external aragonite layer and an internal calcite layer (*Cornish and Kendall*).

Almost all are marine.

Terms used :—

Polypide or *Zooid.*—The individual animal.

Zoarium.—The colonial structure formed by the polypides. Commonly attached or encrusting.

Zoœcium or *Cellule.*—The tube-like or ovoid chamber occupied by each polypide.

Ovicell.—A chamber for containing one or more eggs, from which embryo-polypides develope and are set free. The ovicell forms a swelling above the aperture of certain zoœcia in cheilostomatous colonies, and an inflation between the zoœcia in cyclostomatous colonies.

Operculum.—The cover that closes the aperture of the zoœcium in some polyzoa.

Avicularia and *Vibracula.*—Beak-like and whip-like appendages respectively, set on stalks and arising from little special pits on or between the zoœcia (fig. 58). Used in obtaining food, or for defensive purposes. They are in reality specially modified zoœcia.

A. CYCLOSTOMATA.

Zoœcia tubular, typically not narrowing towards the aperture; no operculum. Calcareous (aragonite with some calcite, *Sorby*); rarely horny.

Entalophora.—Zoarium branching. Zoœcia in the form of long curving tubes, which open all round the surface of the twig-like zoarium. Marine.
Gotlandian to *Recent.*

Fascicularia.—Zoarium spheroidal, fixed at base. Zoœcia tubular, often curving, united into bundles which radiate from the base, leaving hollow interspaces. Marine.
Pliocene.

B. Cryptostomata.

The Fenestellidæ here form the most important family, in which the zoœcia show considerable deviation from the tubular type; in section, they are seen to be more complex and narrowed at the external aperture. The latter is, however, round and simple, as in the typical cyclostomata.

Fenestella (figs. 56 and 57).—Zoarium lamellar, the sheet-like mass being commonly folded into the shape of a funnel, often

Fig. 56. — *Fenestella retiformis* (Permian). Showing form of the zoarium.

Fig. 57.—*Fenestella retiformis* (Permian). Enlarged, to show the zoœcia and the larger interspaces.

several inches across. Built up of rods which radiate from the base and are connected by little cross-bars so as to form a network. The minute zoœcia are grouped in two rows on each of these rods. Sometimes a third central row occurs. The zoœcia must be looked for with a lens; and the far larger interspaces of the mesh are styled *fenestrules.* On the systematic position of this genus see Ulrich, *Geol. Surv. of Illinois*, vol. viii., p. 349. Marine.
Gotlandian to *Permian;* particularly *Carboniferous.*

C. Cheilostomata.

Zoœcia typically ovoid, not tubular; the aperture is in the side and near the upper end, and is smaller than the diameter of the zoœcium.

This aperture was closed by an operculum in most forms. The pits occupied by avicularia and vibracula can often be recognised. Horny or calcareous (aragonite, with some calcite?).

Eschara (fig. 58).—Zoarium formed of two layers of zoœcia, back to back, producing a sheet-like mass which branches as it spreads. Zoœcia close-set, typically cheilostomatous, with pits where the appendages have fallen away; the zoœcia of one row alternate with those of the next. Marine.

Fig. 58.—*Eschara monilifera* (Pliocene); after Busk. The appearance of the aperture varies considerably; in this example the pitted supports of avicularia at each side of the base of the aperture are clearly seen.

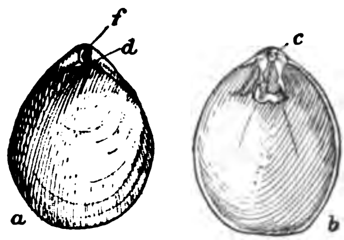


Fig. 59.—Brachiopod (*Terebratula vitrea*, Recent; after Davidson). *a*, The two valves united. *f*, Foramen in beak of ventral valve; *d*, Deltidium. *b*, Interior of dorsal valve, showing the brachial loop. *c*, Cardinal process.

Jurassic to *Recent*.

Lepralia.—Much like Eschara, but forming one encrusting layer. Marine.

Cretaceous to *Recent*.

Membranipora.—Zoarium encrusting. Zoœcia rather flat, with raised margins, and touching one another along their borders, more commonly than overlapping. The front of each is generally lost, having consisted of a chitinous membrane, a wide shallow cavity being thus revealed. Arrangement of zoœcia rather irregular. Marine.

Jurassic to *Recent*.

Cellepora.—Zoarium built up of zoœcia piled irregularly on one another, and thus forming a mammillated aggregate fixed at the base. Sometimes branching. Zoœcia fairly ovoid. Marine. *Cainozoic.*

VI. Brachiopoda.

The Brachiopoda, formerly more prominent than the Mollusca, inhabit a bivalve shell, composed of calcite, or occasionally of phosphate of lime; this is minutely perforated over the whole surface in almost all the families. The Rhynchonellidæ form an important exception, being imperforate (impunctate). Hollow spines, often of great length, project in some genera from the surface of the shell.

The valves of the shell are typically unequal; even if apparently equal, their internal structure is very different. Hold the shell so that the small valve faces the observer, and the umbo of the large valve forms the highest point of the shell; a vertical plane passing through the umbos and the point opposite to them on the lower border divides the shell into two symmetrical halves. Compare Lamellibranchiata. (See fig. 59.)

The modern species, which are numerous and all marine, mostly inhabit deep water.

The modern classification of the brachiopoda is discussed by Schuchert, *Bull. U. S. Geol. Survey*, No. 87 (1897), pp. 113-135. For our present purposes, the two large divisions of Articulata and Inarticulata will prove sufficient.

Terms used:—

Ventral Valve.—The larger valve of the shell; or in any case that covering the ventral portion of the animal.

Dorsal Valve.—The smaller valve, or that covering the dorsal portion.

Both valves are commonly perforated by minute canals, being then said to be *punctate* (fig. 65).

Both show somewhat oval *Muscular impressions*, placed below the hinge. In addition, *Vascular impressions*, indicating the position of blood-vessels in the mantle, are sometimes seen as faint grooves ramifying over the internal surface of both valves; these may appear as ridges on internal casts.

The ventral valve terminates posteriorly in a more or less sharp *Beak* or *Umbo*. An aperture, the *Foramen*, may occur in this, or just below it, serving for the exit of the fibrous pedicle by which the animal was attached. When below the beak, it is generally triangular. In the dorsal valve, the beak is usually less prominent.

Deltidium.—A triangular structure found below, and partly or wholly surrounding, the foramen in many forms. It consists of two little plates, generally meeting along part of their length, and arising from opposite sides below the beak, thus limiting the aperture (fig. 59).

Pseudodeltidium.—A plate formed occasionally across the foramen and spreading anteriorly from the beak.

Area.—The flat area often occurring between the hinge and the beak; sometimes striated. Commonly seen in the ventral valve, rarely also in the dorsal. It stretches on either side of the triangular foramen, the deltidium, or the pseudodeltidium.

Teeth.—Two processes set in the ventral valve, and commonly borne by two "dental plates," which are like short septa rising from the inner surface of the valve. The teeth occur on the *Hinge-line* (or line along which the two valves are united during life). They fit into two sockets in the dorsal valve.

The dorsal valve bears ordinarily a *Cardinal Process* projecting somewhat down from the centre of its hinge-line. To this the muscles that opened the shell were attached. Two plates called *Crura*, one on each side of the centre of the hinge-line, may occur in this valve, the "arms," or lamellar mouth-appendages of the animal, being then attached to them. In most cases they bear a *Brachial Loop*, a calcareous structure of great delicacy, which supports the arms. The loop sometimes is represented by two *Spires*, conically coiled, their apices directed away from or towards the centre of the shell (fig. 64).

Median Septum.—A partition that may be found running for some distance below the hinge-line towards the shell-border, rising from the inner surface of either valve, or both.

The shell-substance of the Brachiopoda (except the occasional phosphatic layers) is very characteristically built up of long curving calcite prisms, among which circular gaps, the perforations, commonly appear. The obliquity of these prisms to the surface of the shell, and their curving, allow their polygonal ends and their lateral faces to be visible at once in microscopic preparations.

A. Articulata (Valves connected by a Hinge). Shell Calcite.

Terebratula (fig. 59).—Shell oval, punctate; often folded slightly at the margin; surface smooth, with mere lines of growth parallel to the margin. Curved hinge-line. Beak pierced by a round foramen, the deltidium occurring below this and not surrounding it. Brachial loop short.

Devonian to *Recent*. Especially *Mesozoic*.

Terebratulina.—Like Terebratula in all essentials, but deltidium small and surface of shell delicately striated by grooves radiating from the apex.

Jurassic to *Recent*.

Magellania (**Waldheimia**).—Not externally distinguishable from Terebratula, but brachial loop long, and a median septum in dorsal valve. *Lias* to *Recent*.

Kingena.—Allied to Terebratula; hinge-line straighter, and brachial loop united to a median septum.

Jurassic and *Cretaceous*.

Pygope.—A Terebratula in which, after a certain age, the lateral parts of the valves grow outwards and then reunite, leaving an aperture through the whole form; this comes finally to lie nearer to the beak than to the growing margin. In casts the vascular impressions are well seen.

Tithonian (*U. Jurassic*).

Stringocephalus (fig. 60).—Shell punctate, and resembling a wide Terebratula, but ventral valve with distinct area; deltidium and pseudodeltidium both present. Strongly developed median septum in ventral valve. Cardinal process long and curved, bifurcating at end to pass on each side of the septum in the

Fig. 60.—*Stringocephalus Burtini* (Devonian). Deltidium missing.

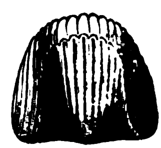


Fig. 61.—*Rhynchonella*. Viewed from below, showing the plicated junction of the closed valves.

opposing valve. Loop curving round parallel to and near the margin of the valve.

Devonian. Known also in *Gotlandian*.

Rhynchonella (fig. 61).—Shell impunctate, rather triangular,

the margin on each side of the beak being straight and the outer margin curved. Ventral valve commonly infolded down the middle line, and dorsal valve bulged out to correspond; margins almost always bent into sharp folds, giving well marked radial ridges down the surface. Beak sharp and bent over downwards and even inwards; foramen below it, commonly surrounded by the deltidium (compare Terebratula). No loop, the crura alone being present.

Ordovician to *Recent.*

Pentamerus (fig. 62).—Allied to Rhynchonella. Shell impunctate, markedly inequivalve, and strongly convex; smooth or furrowed. Beak curved downwards; no deltidium. Median septum in ventral valve strongly developed, dividing on its free edge into two diverging septum-like dental plates, between which a little

Fig. 62.—*Pentamerus galeatus* (Devonian). Showing on the beak the trace of the internal septum.

Fig. 63.—*Spirifer pinguis* (Carboniferous).

chamber is thus formed, open at the end away from the beak. The dorsal valve has two septa, arising one on each side of the central line, which approach the dental plates. The remarkable size of these structures in proportion to the cavity of the shell causes it to break open easily along a surface formed by the ventral septum, one or other dental plate, and the corresponding dorsal septum. The septa can sometimes be traced as lines on the convex exterior of the shell (fig. 62). Casts show characteristic deep grooves in the place of these internal partitions.

Gotlandian and *Devonian.*

Camarophoria.—Like Rhynchonella, but with an internal structure resembling that of Pentamerus on a small scale; one septum in the dorsal valve, dividing on its edge.

Devonian to *Permian;* especially the latter.

Spirifer (fig. 63).—Shell impunctate, commonly with a median ventral furrow and dorsal ridge-like fold as in Rhynchonella; generally also marked with radial grooves. Hinge-line straight, often forming the longest dimension of the shell, and even causing ear-like expansions of the margin just below it. Ventral valve with prominent sharp beak, very commonly curved over; area triangular; foramen triangular, closed over in part by a pseudo-deltidium. Dorsal valve with small narrow area; brachial spires present and highly developed, as may fairly often be seen on breaking open the shell (fig. 64). They occupy almost all the valve, their apices being directed outwards.

S. P. Woodward notes that silicified specimens occur in which

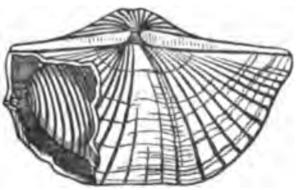


Fig. 64.—*Spirifer trigonalis* (Carboniferous). Broken open to show brachial spire.

Fig. 65.—*Spiriferina Walcottii* (Lias). Showing punctate character.

the spires may be freed by the use of acid from the matter that obscures them.

Gotlandian to *Permian*. Very abundant in species in the *Devonian* and *Carboniferous*.

Spiriferina (fig. 65).—Like Spirifer, but punctate, and with a median septum in the ventral valve. Typically smaller than Spirifer. Perforations can easily be seen with a lens, especially on slightly rubbed specimens.

Carboniferous to *Lias*; typically the latter.

Retzia.—Shell punctate; marked by strong radial ribs. Foramen, with deltidium under it, in ventral valve. Spires in dorsal valve, much as in Spirifer.

The genus, in its usual wide sense, is *Gotlandian* to *Trias*.

Meristella (formerly classed with Athyris).—One of the Spiriferidæ. Shell impunctate, smooth, and resembling in form a wide Terebratula, but without the foramen of that genus, Well marked median septum in dorsal valve; spires similar to Spirifer.

Gotlandian and *Devonian*.

Atrypa.—Shell impunctate, and resembling Rhynchonella, but typically with a straighter hinge-line. Foramen in beak, which

is curved over; deltidium below; no area. Dorsal valve with large spires, their apices directed towards the central part of the inner surface of the valve, and thus nearly touching one another.

Ordovician to *Trias*; especially *Gotlandian* and *Devonian*.

Koninckina.—Form somewhat like Productus; dorsal valve concave. Apices of spires directed outwards.

Trias of Alps.

Orthis.—Shell punctate, commonly approaching a rectangular shape, the valves often almost equal, and both only slightly convex; marked with radial grooves in almost all cases. Hinge-line straight, but shorter than the greatest width of the valve; each valve with an area which is notched in the centre, the two triangular notches together forming the foramen. Strongly marked muscular and vascular impressions. Cardinal process not divided (in some allied genera it is furrowed); brachial crura present, but small, and neither loop nor spires.

L. Cambrian to *Carboniferous*. An extremely abundant genus in the older Palæozoic.

Strophomena.—The Strophomenidæ have received of late considerable revision, on account of variations in the internal characters of species previously grouped under the same genus. Strophomena itself now includes shells without crura (compare Orthis), and with ventral muscular area bounded by raised margin. Ventral valve concave, dorsal convex. (Example:—*Strophomena rugosa.*)

Ordovician.

Leptæna.*—Like Strophomena in general, but with dorsal valve concave, ventral convex, and broad shallow ventral muscular area. The edges of the valves are often bent sharply over in a dorsal direction. Flatter part distinctly wrinkled in concentric folds. (Example:—*Leptæna rhomboidalis.*)

Ordovician to *Carboniferous*. Doubt hangs over all the species recorded from the Lias. Munier-Chalmas finds that some possess brachial spires, and has referred them to a new genus, **Koninckella** (*Bull. soc. géol. France*, 3me. sér., t. viii., p. 279).

Rafinesquina.—Like Leptæna, but without the abrupt bend in the shell, and unwrinkled. (Example:—*Rafinesquina* (*Strophomena*) *alternata.*)

Ordovician.

Productus (fig. 66).—Shell punctate, the perforations being

* See Hall, *Pal. of New York State*, vol viii. (1892), &c.

produced in spines of various lengths. Not attached by a pedicle, as are the preceding genera, but free, or occasionally fixed by the spinose surface of the ventral valve.* Surface

Fig. 66.—*Productus giganteus* (Carboniferous).

sometimes smooth; more commonly ribbed, with hollow spines, set mostly in the neighbourhood of the hinge. Ventral valve strongly convex, with curving beak; dorsal valve concave. No foramen; no hinge-teeth. Hinge-line straight, sometimes forming the greatest width of the shell, with ear-like expansions; sometimes shorter.

Devonian to *Permian*. Especially *Carboniferous*.

B. Inarticulata.

Valves not connected by a hinge, being kept closed by the adductor muscles, and moved apart in a lateral direction by "protractor sliding muscles," so that the apices of the valves are made to diverge from one another sideways, instead of approaching one another on opening, as in the more common brachiopods, the Articulata.

Lingula.—Shell formed of alternating lamellæ of horny matter and phosphate of lime, the former predominating; flexible in modern examples; punctate. Almost equivalve, each valve shaped like a flat shovel, pointed at the beak, truncated on the opposite margin. Smooth, or marked by mere delicate concentric growth-lines. A pedicle emerged between the beaks of the valves.

Ordovician to *Recent*.

Lingulella.—Like Lingula, but with a vertical slit running from the beak of the ventral valve, probably to allow of the

* See R. Etheridge, jun., *Quart. Journ. Geol. Soc.*, 1876, p. 454, and 1878, p. 498.

passage of the pedicle. Muscular impressions stronger than in Lingula.

L. Cambrian to *Ordovician.*

Obolella.—Shell built up like that of Lingula, but with phosphate of lime preponderating over the horny layers. Form approaching circular, nearly equivalve; valves only slightly convex, and concentrically marked. The beak of the ventral valve is furrowed on the inner side by a groove for the pedicle. Differs from **Obolus** only in form and position of muscular impressions, those near the centre of the valve in Obolella being widest at the end away from the beak, while in Obolus this end is narrowest.

Both genera have the same range, *Cambrian* and *Ordovician.*

Discina (fig. 67).—Shell minutely punctate, composed mostly of horny matter. Inequivalve. Form circular, smooth or concentrically marked. Ventral valve flat or slightly conical, with beak almost central; a foramen occurs close against the beak in adult forms, and from it a furrow sometimes runs externally towards the margin. Dorsal valve conical, with an excentric beak. The forms with a furrow have been called **Orbiculoidea**, and those with a ventral median septum **Discinisca**, leaving Discina only for Recent species. In its usual wider sense, Discina is *Cambrian* to *Recent.*

Fig. 67.—*Discina Forbesii* (Wenlock Beds).

Fig. 68.—*Crania parisiensis* (Senonian). Interior of ventral valve.

Crania (fig. 68).—Shell showing punctation on inner surface only, the tubules breaking up into a number of much more minute ones as they near the outer surface. Calcareous and fairly thick; sub-rectangular to circular; surface smooth, or ribbed with ridges radiating from the beaks. Ventral valve conical and attached by the actual shell-substance of the beak, which is commonly nearly central. Dorsal valve conical, also with nearly central beak. Both valves have well developed muscular impressions and a characteristic broad flat border marked by granulations. The ventral valve is naturally often found adherent to other fossils, without the dorsal valve.

Ordovician to *Recent.*

CHAPTER XXIV.

FOSSIL GENERIC TYPES.

VII. Lamellibranchiata.

In contrast with those of the Brachiopoda, the bivalve shells of these animals have typically equal valves. Moreover, hold the shell so that one valve faces the observer and the umbos form the highest point; a vertical plane passing through the umbos, and perpendicular to the plane of junction of the valves, will divide the shell into two unequal parts. Hence the shells are

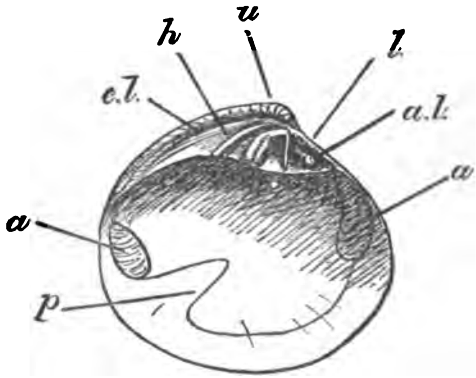


Fig. 69.—Sinupalliate Lamellibranch (*Cytherea incrassata*, Oligocene); left valve. *a*, Impressions of the adductor muscles. *a.l.*, Anterior lateral tooth. *e.l.*, Groove for the external ligament. *h*, Hinge, with three diverging cardinal teeth; the middle one is divided by a groove. *l*, Lunule. *p*, Pallial line; the infold or sinus indicates the position of the retractor muscle of the siphons. *u*, Umbo.

said to be *equivalve* but *inequilateral*. The longer part is in almost all cases the posterior.

One or other valve may become smaller; but in these inequivalve genera the inequilateral character will probably betray itself (fig. 72). Similarly some genera have shells that are practically equilateral; but a slight difference of the hinge-line on either side of the umbo (fig. 91), or the posterior position of the single internal muscular impression, will often serve as a guide.

The classification here adopted seems suited to those who unfortunately have to deal with empty shells rather than with living molluscs; but it must not be regarded in all cases as an expression of the nearest zoological alliances. The separation

of Leda and Nucula is a marked illustration of this. (See the interesting discussion by F. Bernard, *Paléontologie*, pp. 541-543.)

Terms used :—

Anterior Border.—The end of the shell where the mouth and foot were situated.

Posterior Border.—The end of the shell where the cloacal aperture and, in siphonate forms, the siphons, were situated.

Umbo.—The beak or apex of either valve. This in the majority of forms is directed forwards—*i.e.*, towards the anterior end. Sometimes bent round or even pointing posteriorly.

Hinge-line or "Hinge-border."—The line along which movement takes place when the valves open.

Ventral Border.—That opposite to the hinge-line.

Right and Left Valves.—The shell is held resting upon its ventral border, and the anterior border of the shell is directed away from the observer. The "right" valve is then to his right, the "left" valve to his left.

Ligament.—The "external ligament" (by which the valves would be opened unless held closed by the muscles within) is placed, in the main, posteriorly to the umbos, and sometimes leaves an impression above this part of the hinge-line. The "internal ligament," or "cartilage," lies within, below the hinge-line, and is set in *ligamental grooves* or *pits* (figs. 84 and 93), which are seen near the hinge when the animal matter has disappeared. It may be remembered that the internal ligament becomes compressed when the valves close, and that its expansion causes them to open directly the muscular pull is released. Sometimes only one of the ligaments is present.

Area, or *Escutcheon.*—A generally elongated oval area seen behind the umbos in some genera, when the valves are united, and running some way along the hinge-line.

Lunule.—An oval area seen, when the valves are united, in front of the umbos.

Gaping.—When the valves are closed, and yet leave an opening at one or both ends, the shell is said to be gaping.

The following structures must be noticed on the interior of the valves :—

Cardinal Teeth.—One or more processes, fitting into sockets in the opposing valve, and arising near the centre of the hinge-line. The teeth thus alternate in opposite valves. The true cardinal teeth arise below the umbo, but may extend back obliquely from it, so as to stimulate lateral teeth.

Lateral Teeth.—Similar processes commonly ridge-like, towards the anterior or posterior end of the hinge (figs. 69 and 73).

Muscular Impressions.—These are shallow, fairly circular, or

pear-shaped pits representing the surfaces of attachment of the adductor muscles, or muscles used in keeping the shell closed. Sometimes only one (the posterior), sometimes two, are present in each valve. When the two impressions are fairly equal in area, the shell is that of a *Homomyarian;* when the anterior impression is smaller, it is that of a *Heteromyarian.* The animals with only one adductor muscle are said to be *Monomyarian.*

Pallial Line.—This is a faint impressed line, parallel to the border of the valve and a little way within it, representing the line of attachment of the muscles that are placed near the edge of the mantle. If it is continuously convex outwardly, the shell is said to be *integripalliate.* If it is more or less indented by a pallial sinus, the shell is *sinupalliate.*

Pallial Sinus.—An infold of the posterior portion of the pallial line, sometimes a mere shallow curve, sometimes deep and extending back even beyond the centre of the valve. This occurs only in forms which can extend and retract their siphons.

The structure of the shell-substance itself exhibits two layers, the whole being covered in life by a skin, or "periostracum." The outer layer, sometimes thick, sometimes thin, consists of calcareous prisms in contact along their walls. Here and there a polygonal interspace occurs. The fibrous structure seen on cross-fracture of Inoceramus is due to well-developed prisms of this nature.

The inner layer is formed of delicate, compact, and pearly lamellæ, sometimes accumulated to a great thickness. These layers occasionally leave irregular interspaces or chambers of flattened and curving form, as in the thickened region near the umbos of some oysters.

The shell-substance is sometimes calcite, but most commonly aragonite. Or, when both minerals are present, the outer layer consists of calcite, the inner of aragonite. The mineral constitution of the shells of many genera yet awaits investigation, and the usual alteration of aragonite in old forms into granular calcite precludes certainty of determination in some extinct examples.

The lamellibranchiata are mostly marine; the fresh-water types referred to will be specially indicated. Some genera are attached to the sea-floor by the shell itself; others by fibrous outgrowths, the *byssus,* issuing near the umbos; others are free and locomotive. A few lamellibranchs, of different families, bore into mud, wood (as Teredo, the ship-worm), or into other shells, corals, or even the hardest stone (as Pholas and Lithodomus); the cavity thus made is called a *crypt,* and is increased until the animal and shell attain their full development. Thus the animal cannot leave the cavity, communication being kept up with the exterior through the narrow opening which repre-

sents the first stage of the boring. The siphons are turned upwards, the anterior end of the animal being downwards, and a calcareous siphonal tube is sometimes developed, the small shell-valves becoming dwarfed by comparison and incorporated with the tube, and the whole shell thus appearing cylindrical. Aspergillum is one of the most remarkable examples.

Boring shells are often represented merely by casts of their crypts, which are often club-shaped, the short handle of the club being the result of the infilling of the narrow entry to the cavity.

Fossil siphonate shells are occasionally found—and should be looked for—in the position in which they lived in the soft mud which ultimately entombed them; their umbos are thus directed downwards, and their siphonal ends upwards, in the stratum.

A. Homomyarian Siphonate forms with Pallial Sinus (Sinupalliate).

The adductor muscular impressions are two in each valve, one posterior, one anterior, and fairly equally developed. The animal possessed long retractile siphons. In certain exceptional families these siphons are encased in a calcareous tube projecting far beyond the limits of the valves.

Cytherea (fig. 69).—Shell thick, approximating to circular, umbo well forward, with lunule. Generally concentrically marked. Three diverging well developed cardinal teeth in each valve. An anterior lateral tooth in left valve. Pallial sinus acute-angled, moderately developed. Inner margin of shell smooth.

Cretaceous to *Recent.*

Venus.—Like Cytherea, but without lateral tooth, and commonly with delicately grooved inner border.

Jurassic to *Recent.*

Tellina.—Slightly inequivalve. Shell thin, elongated oval, rounded anteriorly, more acute behind. Umbos almost in centre. Concentrically marked. Hinge narrow; in each valve two cardinal teeth, and commonly an anterior and posterior lateral tooth. Sinus very broad and deep (fig. 70).

Cretaceous to *Recent;* this genus is particularly rich in living species.

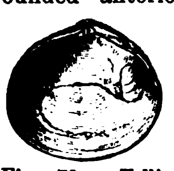


Fig. 70. — *Tellina* (Post - Pliocene). Right valve, showing the large pallial sinus.

Panopæa (Glycimeris).—Shell thick, often large, and approaching an elongated rectangle. Gaping at both ends. Umbos rounded and placed well forward. Concentrically marked. One cardinal tooth in each valve.

Note.—The limits of this genus are somewhat obscure.

Cainozoic. Many older forms referred to Panopæa are now placed with the Pholadomyidæ (Gresslya, &c.)

Pholadomya.—Shell thin, elongated or obliquely oval, markedly convex; gaping behind and sometimes in front. Anterior border a little truncated. Umbos well forward. Escutcheon sometimes present. Marked with knotty radial ribs, particularly on the anterior surface; also with more delicate concentric lines. Practically toothless, one obscure process occurring in each valve. Sinus broad and fairly deep. The thinness of the shell makes casts alone commonly met with.

Lias to *Recent.* Characteristically *Jurassic.*

Goniomya.—Like Pholadomya, but marked with rather delicate ribs, forming Vs, the angle of which is directed towards the middle of the ventral border.

Especially *Jurassic.*

Homomya.—Like Pholadomya, rather elongated, gaping at both ends, but with only concentric striations.

Trias to *Cretaceous.*

Gresslya.—Also one of the Pholadomyidæ. Elongated oval, much like the longer Pholadomyas, but right valve somewhat larger than left, the umbo rising higher. Umbos well forward; lunule present, no escutcheon. Concentrically marked. No teeth. Right valve with a ridge running along the hinge-line from the umbo posteriorly, which leaves a furrow in the casts that frequently occur. Compare Ceromya.

Trias to *Jurassic.*

Ceromya (**Isocardia** in part).—Inequivalve, sometimes the right, but more commonly the left valve being slightly the larger, the umbo rising higher, as in Gresslya, and the posterior border overlapping that of the other valve. Approximating to circular, strongly convex, slightly gaping. Umbos large and well rounded; lunule feeble or absent. Concentrically marked. No teeth. Ridge in right valve, as in Gresslya. Commonly found as casts.

Typically *Middle and Upper Jurassic.*

Mactra.—Shell fairly thick, approximately triangular, rounded in front, more pointed behind; gaping slightly posteriorly. Concentrically marked. A cardinal tooth in each valve, bifurcating, and thus shaped like an inverted **V**; behind it, and still under the umbo, a triangular pit, which marks the position of the cartilage or internal ligament. A second cardinal tooth, of lamellar shape, is sometimes present. Anterior and posterior lamellar lateral teeth well marked, those of the right valve being

double—*i.e.*, consisting of two parallel ridges running along the hinge-line. Sinus shallow.

Middle Jurassic to *Recent*. Especially *Cainozoic*.

Mya (fig. 71).—Inequivalve, left valve the smaller. Elongated, somewhat oblong; gaping markedly at both ends. Umbos

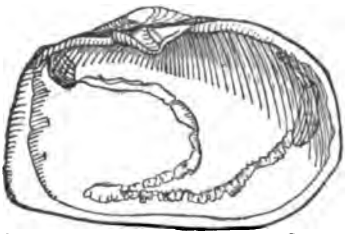


Fig. 71.—*Mya truncata* (Post-Pliocene). Left valve, showing the large spoon-like process beneath the umbo.

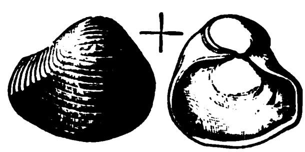


Fig. 72.—*Corbula pisum* (Oligocene). Showing inequivalve character.

approaching centre of margin. Concentrically marked. Left valve with a well developed spoon-like process under the umbo, for the attachment of the cartilage. Right valve with one small cardinal tooth. Sinus large and deep; pallial line often shows strong subsidiary impressions running upwards from it.

The Myas burrow into sandy mud, particularly near the shore.

Miocene to *Recent*.

Corbula (fig. 72).—Ally of Mya. Inequivalve, left valve much the smaller. Shell small, oval, produced posteriorly, ending there with rather a straight border; not gaping. Concentrically marked. One cardinal tooth in right valve; left valve with a process much like that of Mya, which fits into a groove behind the tooth of the right valve. Sinus quite shallow.

Marine or Estuarine.

Trias to *Recent*. Especially *Cainozoic*.

Leda.—Shell small, elongated and narrowed posteriorly, with umbos directed backwards. Hinge-line bent, with numerous transverse teeth, as in Nucula, with which Leda should be compared (see fig. 80).

Gotlandian to *Recent*.

Teredo.—One of the Pholadidæ; the so-called ship-worm. Shell small, each valve three-lobed, the central lobe the longest. Concentrically striated. No true hinge or ligament, the valves being quite subsidiary to the great siphonal tube, which extends far beyond them.

The borings of this mollusc are tubular like those of worms, but typically somewhat straighter; they are found commonly in fossil wood, as in the London Clay, either empty or infilled with mud or crystalline deposits.

Lias to *Recent*. Especially *Cainozoic*.

B. Homomyarian Siphonate forms without Pallial Sinus (Integripalliate).

The adductor muscular impressions are two in each valve, as in the preceding group, and the absence of the pallial sinus makes the interior of the valves resemble those of homomyarian asiphonate forms. The siphons of the animal were not retractile.

Cardium.—The common Cockle. Shell fairly thick, approximately circular, or elongated in a vertical direction; sometimes slightly gaping behind. Umbos rather large and rounded. Radially ribbed, the ribs commonly ornamented with protuberances. Two cardinal teeth and an anterior and posterior lateral in each valve (fig. 73). Inner border notched.

Forms with radial markings on the posterior part only, and concentric on the remainder, have been sometimes divided off under the name **Protocardia**.

Rhætic to *Recent*; especially *Cainozoic*.

Conocardium (fig. 74).—Shell heart-shaped when viewed from

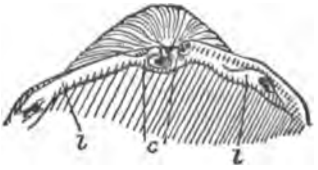


Fig. 73. — Hinge of *Cardium edule* (Recent). Left valve. *c*, The two cardinal teeth. *l*, The ridge-like lateral teeth.

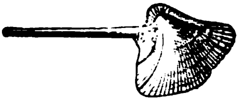


Fig. 74.—*Conocardium aliforme* (Carboniferous).

the front, but somewhat elongated behind; strongly convex. The anterior end is truncated, the umbo being close to it; just below the umbo a tube-like prolongation of the shell runs out in continuation of the hinge-line. Gaping at the posterior end.

Radially marked; margins sharply folded by the ridges and furrows. Almost toothless.

Gotlandian to *Carboniferous.*

Cyrena (fig. 75).—Shell thick, oval, sometimes rather acute posteriorly. Concentrically marked. Three cardinal teeth and an anterior and posterior lateral in each valve. Sometimes a slight pallial sinus. In the sub-genus **Corbicula** the lateral teeth are elongated and transversely striated.

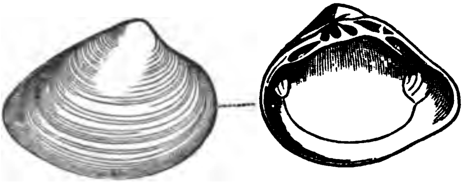


Fig. 75.—*Cyrena cuneiformis* (Lower London Tertiaries).

Brackish or fresh-water at present day, but often associated at river-mouths with typically marine shells, and hence of little value as a guide to conditions of deposition.

Lias to *Recent.*

Cyclas (Sphærium).—Ally of Cyrena, but shell thin and nearly equilateral. One feeble cardinal tooth in right valve and two in left. Lamellar anterior and posterior lateral teeth. **Fresh-water.** The reference of Wealden species to this genus has been criticised, though very generally made. Sandberger quotes the earliest Cyclas as *Eocene*, referring older forms to Cyrena, &c.

Cyprina.—Shell thick, oval, resembling Cytherea; markedly convex. Concentrically striated. Two cardinal teeth and one posterior lateral tooth in each valve. There are also two feeble anterior lateral teeth in the right valve; and in the left valve one anterior lateral (*Fischer*).

Lias to *Recent.*

Fig. 76. — *Astarte elegans* (Inferior Oolite).

Astarte (fig. 76).—Shell thick, approaching circular at times, at others obliquely elongated. Umbos rather pointed; lunule generally present. Concentrically marked. Two cardinal teeth in each valve; no laterals.

Lias to *Recent.* Especially *Cainozoic.*

Cardita.—Shell thick, somewhat like Cardium, but occasionally elongated. Umbos well forward. Radially ribbed. Inner border notched. Two elongated cardinal teeth, and a feeble anterior lateral, in right valve; two divergent cardinal teeth, and one feeble posterior lateral, in left valve. (As to difficulty in reading teeth in Cardita, see Fischer, *Conchyliologie*, p. 902.)
Trias to *Recent*. Especially *Cainozoic*.

Venericardia.—Much like Cardita. Two oblique cardinal teeth, and a feeble anterior lateral, in right valve; two cardinal teeth and one long lamellar posterior lateral in left valve. Interior of margin of shell distinctly notched.
Eocene to *Recent*.

Crassatella.—Shell decidedly thick, oval, truncated slightly at posterior margin. Lunule present. Three cardinal teeth in right, two in left valve; an anterior and posterior lateral in both. Pit for cartilage immediately below the umbos, and behind the middle cardinal tooth of the right valve.
Cretaceous to *Recent*. Especially *U. Cretaceous* and *Eocene*.

Cardinia.—Placed by S. P. Woodward near Cardita, by other authors as an asiphonate form near Unio. Shell elongated, oval, flattened at the sides. Umbo well forward. Concentrically marked. Two cardinal teeth in left valve, one in right, their feeble development being a characteristic feature; anterior lateral tooth in right valve, elongated posterior lateral in left, well developed.
Jurassic. Especially *Lias*.

Chama.—Inequivalve; commonly attached by the umbo of the left valve, the upper valve, which is therefore generally the right, being the smaller. Shell thick, almost circular. Umbos of both valves bent forward and curved over, as if about to coil spirally. Concentrically marked, the successive shell-layers protruding beneath one another with irregularly serrated edges, giving the surface a foliaceous appearance. One stout cardinal tooth in upper valve, two in lower, between which the first-named fits.
Lower Cretaceous to *Recent*. Especially *Cainozoic*.

Diceras.—Slightly inequivalve; attached by umbo of one or other valve. Shell thick, approximately circular. Umbos very prominent, each being spirally curved and recumbent, as it were, against the surface of the shell. Concentrically marked. Right valve with one cardinal tooth, somewhat flattened and folded;

also a smaller tooth near the anterior end of the hinge. Left valve with one curving tooth, which is elongated parallel to the border. The curved muscular impressions are bounded by ridges, which leave spiral grooves on the casts that often occur; these grooves run almost vertically down towards the edge representing the margin of the valves. In such casts the umbos appear still more distinctly prominent, the spiral turns of the internal moulds not being in contact with one another.

M. and U. Jurassic (*Tithonian*).

Fig. 77.—*Hippurites* (Senonian). Left (opercular) valve removed.

Hippurites (fig. 77).—This extraordinary shell, a representative of an altogether exceptional family, the Rudistæ, is now regarded as allied to Diceras and the other Chamidæ, particularly through Monopleura, in which one valve is conical and the other like an operculum fitting on it. In Hippurites the shell is also very inequivalve, the lower valve, which is the right, being conical, or more often cylindrical, terminating in a cone at the base. This valve is vertically furrowed and ribbed. Left valve small and flattish, strewn over with the small apertures of canals which perforate the shell; radially ribbed in most cases, with central umbo; resembles an operculum when closed down on the large right valve. The interior of the left valve bears long vertical processes corresponding to teeth, which fit into deep sockets in the lower valve. The chamber in which the animal lived is quite small, the lower part of the shell being filled up by the deposit of the inner shell-layer, which produces a succession of irregularly curving partitions, with interspaces. A similar infilling occurs within the long umbos of certain oysters.

In some allied forms, as **Radiolites**, the outer prismatic shell-layer presents on fracture a coarse structure of hollow rectangular cells.

The resemblance that the shells of Hippurites, &c., bear to

corals is sometimes increased by their clustering together and growing up side by side in groups.

Entirely *Cretaceous;* particularly in the higher beds.

C. Homomyarian Asiphonate forms (Integripalliate).

The animal does not possess distinct siphons. The impressions of the anterior and posterior adductor muscles are practically of the same size. Shell typically equivalve.

Arca (fig. 78).—Shell thick, approaching rectangular; markedly convex. Umbos prominent and rounded, with a triangular striated area between them and the hinge-line, forming a surface of attachment for the ligament during life. Radially marked. Straight hinge-line. Teeth very numerous in each valve, forming well-marked short transverse ridges on the broad surface of the

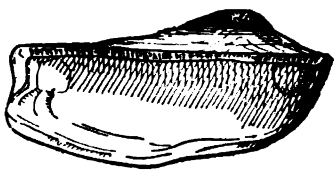


Fig. 78.—*Arca Noæ* (Recent). Left valve, showing area beneath the umbo, and the numerous hinge-teeth.

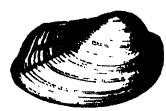


Fig. 79.—*Cucullæa Hardingii* (Devonian).

hinge, the series extending on each side of the umbo nearly to the lateral margins.

Pre-eocene forms are perhaps more allied to Parallelodon.

Ordovician (?) to *Recent.*

Cyrtodonta (Palæarca).—Close ally of Arca; umbo near anterior border. Some of the teeth lie beneath the umbo, others are set near the posterior part of the hinge. Concentrically striated.

Cambrian to *Devonian.*

Cucullæa (fig. 79).—Like a stout Arca in form; but the teeth nearest the anterior and posterior margins are set parallel to the hinge-line, forming horizontal ridges. Concentrically striated.

Devonian to *Recent.* Especially *Mesozoic.* Whidborne, *Pal. Soc.*, "Devonian Fauna," vol. iii. (1898), p. 109, includes two Devonian species.

Parallelodon (Macrodon).—Much like Cucullæa, but umbo more anterior, and anterior teeth transverse, posterior parallel to hinge-line and ridge-like.

Devonian to *Eocene*. Especially *Carboniferous*.

Pectunculus.—Shell thick; valves almost circular and equilateral. Triangular ligamental surface as in Arca. In most species radially and rather delicately marked. Hinge-line curved, with numerous transverse teeth, those nearest the centre being obliterated as the shell approaches old age. Inner margin of valves notched. Shell aragonite (*Cornish and Kendall*).

Lower Cretaceous to *Recent*. Especially *Cainozoic*.

Cardiola.—Form intermediate between a typical Arca and a Pectunculus. Umbos distinctly anterior and slightly twisted. Ligamental surface under them as in Arca and Pectunculus. Surface furrowed radially and concentrically, so as to give a nodose aspect. Hinge-line straight. Believed to be toothless. The alliance of this shell with the Arcidæ is fairly clear, despite the obscurity as to its teeth.

Gotlandian and *Devonian*.

Nucula (fig. 80).—Shell small, somewhat triangular, the umbo forming the apex. The umbos point backwards, the smaller half of each valve being thus, by an exception, posterior.* Hinge-

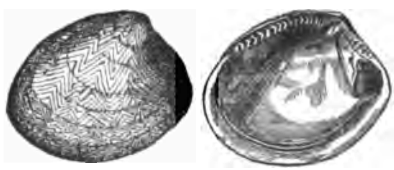


Fig. 80.—*Nucula Cobboldiæ* (Post-Pliocene). The right valve shows the numerous hinge-teeth and the cartilage-pit.

border forming two lines diverging from the umbos; the teeth resemble those of Arca, and are set along the two diverging lines of the hinge. A pit for the cartilage occurs under the umbo. Concentrically or radially marked. Compare Leda, p. 327.

Gotlandian to *Recent*.

Trigonia.—Shell thick, typically rather angular at umbo, rounded anteriorly; drawn out, but finally truncated, behind. Umbo bent slightly backwards. A large area or escutcheon is commonly formed on the posterior surface, bounded on each valve by a fold, which runs from the umbo to the lower point

* On this point see Verrill and Bush, *Am. Journ. Sci.*, ser. 4, vol. iii. (1897), p. 52.

of the truncated border. A subsidiary escutcheon is formed within this by another pair of folds, which occur much nearer to the hinge-line. Marked with nodose radial (rarely concentric) ribs, which are generally coarsely developed. The posterior area above described is often smoother than the rest of the surface, and is marked by striæ parallel to the truncated border. Two diverging plate-like cardinal teeth in right valve, with parallel grooves on their broad surfaces; one strong central tooth in left valve, with a feebler tooth on each side of it.

When the shell is lost, the fossil forms are represented by casts, in which the nodose ribs are wanting. Hence the characteristic form, and particularly the impressions of the furrowed teeth, must be taken as a guide.

Trias to *Recent*. Very rare in *Cainozoic;* abundant in *Jurassic.*

Schizodus.—Form much like a small Trigonia. Surface smooth. Teeth like Trigonia, but not furrowed.

Typically *Permian.*

Myophoria.—Form somewhat like Trigonia, with an external ridge and furrow running obliquely from the umbo to the junction of the ventral and posterior borders. Smooth, or ribbed concentrically or radially. Teeth as in Trigonia, but the anterior one in the right valve is not furrowed.

This genus is with difficulty separated from Trigonia, but the shells are typically smaller and not nodose. Nor is the umbo so angular as in Trigonia.

Trias.

Unio.—Shell fairly thick, elongated oval, and sometimes approaching a parallelogram. Umbos well forward. Commonly rather smooth, concentrically marked. Two irregular teeth in each valve; these are followed by one posterior lateral tooth in right valve, and by two in left, elongated parallel to the border. **Fresh-water.**

Trias to *Recent;* especially abundant at the present day.

Anodonta.—Shell thin; otherwise like Unio, but devoid of teeth. **Fresh-water.**

Cainozoic.

Archanodon.—Early ally of Anodonta. Probably toothless. *U. Devonian* (*A. Jukesii*), in passage-beds to Carboniferous.

Carbonicola (Anthracosia).—Outwardly has some resemblance to Cardinia. One cardinal tooth in each valve; no laterals. Probably **Fresh-water** (Hind).

Coal-Measures.

Orthonota.—Elongated, oval; umbos near anterior end; well

marked lunule. One or two folds run obliquely from each umbo to the base of the posterior margin. Hinge-line straight, with one or two small cardinal teeth. Of somewhat doubtful affinities.

Ordovician and *Gotlandian*.

Note.—**Grammysia** is closely allied, but its muscular impressions would arbitrarily remove it to the heteromyaria. It is characterised by absence of teeth and by two or more grooves and ridges running from the umbo to the base of the posterior margin, and forming a broader or narrower band across the concentrically striated shell or across its casts. The form is thus much like Orthonota; also like Modiola. *Gotlandian* and *Devonian*.

D. Heteromyarian Siphonate forms without Pallial Sinus (Integripalliate).

For muscles, see section E below.

Dreissensia (Dreissena).—Though a siphonate form, this is a close ally of Lithodomus and Modiola. Shell like Mytilus, or approximately quadrilateral, with an anterior opening between the valves for the byssus. Hinge-line samewhat curved; umbos terminal. Often a fold, as in Modiola, runs from the umbos towards the base of the posterior margin. Smooth, or concentrically marked. One or two feebly developed cardinal teeth, accompanied below the umbo by a plate which bears an impression of the anterior muscle. Inner shell-layer absent.

Fresh and Brackish Water.

Eocene to *Recent*. Especially *Miocene* and *Pliocene*.

Congeria.—A marine ally of Dreissensia, with a small process for pedal muscle behind anterior muscular impression.

Cainozoic and *Recent*. Abundant in the shallowing *Miocene* and *Pliocene* seas of Europe.

E. Heteromyarian Asiphonate forms (Integripalliate).

The impression of the anterior adductor muscle is much smaller than that of the posterior. Shell often inequivalve.

Avicula.—Inequivalve, the left valve more convex than the right. Typically rather small; obliquely oval, often resembling the shape of an insect's wing. Straight hinge-line; umbo not very prominent. The shell is expanded posteriorly under the hinge-line to form a well-marked ear; a much smaller ear, notched for the exit of the byssus by which the animal was attached, occurs in front of the umbo. Commonly marked radially. One feeble cardinal tooth, and sometimes a long posterior lateral tooth, in each valve. Cartilage-pit broad.

Ordovician to *Recent*; but characteristically *Mesozoic* and *Cainozoic*.

Pterinea.—Much like Avicula, but with larger posterior ear, and a number of short hinge-teeth; three or more elongated

posterior lateral teeth run obliquely from under the umbo towards the centre of the large posterior ear.

Ordovician to *Carboniferous*. Mostly *Devonian*.

Posidonomya (fig. 81).—Equivalve. Shell thin and laterally compressed. Obliquely and rather broadly oval. Umbos not prominent; hinge-line short and straight, without true ears. Concentrically marked. No teeth. See Estheria (Phyllopoda).

Ordovician to *Jurassic*. Especially *Carboniferous*.

Monotis.—Equivalve; typically small; form much like Posidonomya, but with a small rounded anterior ear and a more marked posterior one. Radially marked. No teeth.

Trias.

Daonella.—Ally of Monotis. Form rather semicircular, with a fairly long straight hinge-line. No ears. Umbos almost central and not prominent. Radially marked. No teeth.

Trias.

Inoceramus (fig. 82).—Somewhat inequivalve. Varying much in size, some species measuring two feet or more across. Form obliquely oval, with a straight hinge-line. Umbos fairly prominent, sometimes twisted, and set well forward. Concentrically and boldly furrowed; rarely radially furrowed. The hinge-border bears, when viewed from within, numerous closely-set cartilage-

Fig. 81.—*Posidonomya Becheri* (Carboniferous).

Fig. 82.—*Inoceramus Cuvieri* (Senonian). Right valve.

pits, which lie transversely to the length of the hinge. No teeth. Compare Perna below.

The outer layer of the shell is commonly well preserved in the species from the Chalk, though not in those from the Gault; it is easily recognised, even in fragments, by its fibrous cross-fracture (see p. 324) and is often 5 mm. thick. The inner surface of these fragments is seen to be smooth and slightly undulating.

A sub-genus Actinoceramus (fig. 83) has been established for the singular species with deep radial furrows; but transitional forms occur.

Fig. 83.—*Inoceramus* (*Actinoceramus*) *sulcatus* (Gault).

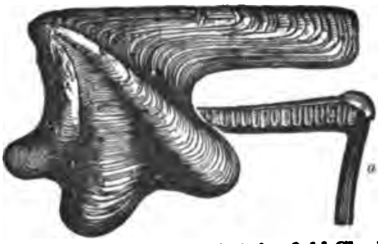


Fig. 84.—*Perna Mulleti* (Atherfield Clay). Showing (*a*) the series of ligament-pits in the hinge-line, which is in this species exceptionally produced.

Mesozoic. Especially *Cretaceous.*

Perna (fig. 84).—Sometimes markedly inequivalve. General resemblance to Inoceramus. Sometimes elongated posteriorly, but often approximately quadrilateral, with rounded ventral border. The umbo, which is acute, is set at the anterior end of the straight hinge-line. Concentrically marked. Numerous transverse ligamental pits. Toothless. Material of shell foliaceous.

Trias to *Recent.*

Gervillia.—Inequivalve; resembling a much elongated Avicula. Hinge-line straight, with a very small anterior and a larger posterior ear. Umbo terminal, like a mere anterior rounding of the hinge-line. Concentrically marked. Oblique ridge-like teeth, running posteriorly; in sub-genus **Hoernesia** one cardinal tooth in each valve. Cartilage-pits conspicuous, broad, and set at some distance from one another.

Trias to *Eocene.* Typically a *Mesozoic* genus.

Pinna.—Shell thin, elongated, each valve triangular in form; gaping behind, so that the whole shell is wedge-shaped. Hinge-line long and straight; umbos terminal. Marked with fine concentric lines. No teeth.

The inner shell-layer is thin, and is composed of aragonite; the prismatic (calcite) layer is thus particularly prominent. In the allied genus **Pinnigena** or **Trichites** (of *Jurassic* and *Lower Cretaceous* age) the prismatic fragments are found an inch or more in thickness.

Devonian to *Recent.* Especially *Cretaceous.*

Mytilus.—The common marine mussel. Shell rather thin;

elongated and approaching triangular, pointed in front, rounded behind. Smooth, or concentrically (rarely radially) marked. Hinge-line straight, umbos terminal. Sometimes one or two obscure cardinal teeth.

The modern mussels live near the shore-line, becoming uncovered at low water, and are attached, often to one another, by a coarse byssus. The inner shell layer is aragonite.

Trias to *Recent.*

Modiola (fig. 85).—Bears some resemblance to Mytilus, but in form approaches an elongated rectangle; the posterior end is more rounded than the anterior, and a broad fold often runs obliquely from the umbo to the base of the posterior margin. Umbos not quite terminal; hence this region of the shell has none of the triangular appearance so characteristic of the anterior end of Mytilus. Concentrically (rarely radially) marked. No teeth.

Fig. 85.—*Modiola Fittoni* (Purbeck Beds).

The modern Modiola is burrowing in habit, or forms a nest around it of fragments of sand, shells, &c.

Devonian to *Recent.* Especially *Jurassic.*

Lithodomus. — Close ally of Modiola. Shell cylindrical, narrowed behind, not greatly elongated. No teeth.

Burrows into stones (as at the famous Temple of Serapis), corals, &c., forming crypts which yield club-shaped casts (see p. 324).

Carboniferous to *Recent.*

Note.—For Dreissena, an ally of the above series, see p. 335.

Fig. 86.—*Hippopodium ponderosum* (Lias).

Hippopodium (fig. 86).—Shell very thick and massive; form somewhat like Modiola. Lunule present. Coarsely and concentrically furrowed. One thick oblique cardinal tooth in each valve. The muscular impressions cause the genus to be here placed with the Heteromyaria; but S. P. Woodward regarded Hippopodium as "a ponderous form of Cypricardia or Cardita."

Lias.

F. Monomyarian Asiphonate forms (Integripalliate).

The shell is closed in the adult by one adductor muscle, which leaves a nearly central impression, placed rather towards the posterior side. It is always the anterior muscle that has disappeared. Except where specially mentioned, the members of this sub-group are toothless in the adult condition. Shell often inequivalve, and commonly attached by one or other valve. Hence, when loosened, the lower valve may reveal an outer scar of very various form, sometimes representing, as an external mould, another shell on which the young animal had become fixed. Occasionally in the Ostreidæ the young shell lies on some surface with prominent markings, such as that of Trigonia or Cidaris, and both valves become folded to suit the curves of the support. As growth proceeds, the nacreous layer is constantly being added to within, while the shell is also spreading at the margins; thus the original portions bearing the impress of the support become separated by new material, and form strangely marked umbos to the shell. The impressions are thus convex on the upper valve, concave on the lower; while within no trace of them is to be seen.

Ostrea (fig. 87).—Attached by left valve. Shell rather inequivalve, composed of foliaceous layers; often thick, especially near the umbos. Form rather flat, lower valve more convex. Irregularly rounded at ventral margin, more acute at dorsal, the umbos being nearly central on the hinge-line. Umbo of left

Fig. 87.—*Ostrea expansa* (Portlandian). Showing thickened character of the shell and the single muscular impression.

Fig. 88.—*Alectryonia frons* (Cretaceous).

(lower) valve more prominent than that of right. Concentrically marked, with sometimes broad irregular radial foldings. A well-marked triangular cartilage-pit occurs below the umbo. Shell composed of calcite (*Sorby*).

Trias to *Recent*. Doubtfully *Carboniferous*.

Alectryonia (fig. 88).—A genus cut off from Ostrea to include forms with bold angular ribs and furrows in both valves, the

margins becoming consequently acutely folded, and the space occupied by the animal being much restricted in volume.

Trias to *Recent;* especially *Cretaceous.*

Gryphæa.—Free, or attached only by umbo of left valve. Shell inequivalve, thick, oyster-like. Nearly equilateral. Left valve strongly convex, with umbo bent over and inwards; right valve smaller, flatter, or even concave, and sometimes reduced to the appearance of an operculum. The form of the shell varies considerably, being, like Ostrea, sometimes expanded and approaching circular, sometimes much narrowed. Concentrically marked.

Lias to *Recent;* especially *Jurassic* to *Lower Cretaceous.*

Exogyra (fig. 89).—Much like Gryphæa, but both umbos twisted backwards almost spirally. Fixed by left valve, which is the larger.

Jurassic to *Cretaceous.*

Fig. 89.—*Exogyra sinuata* (L. Cretaceous). Showing twisting of the umbos.

Lima.—Free, or attached only by byssus. Shell thin, equivalve; obliquely oval, slightly convex, gaping at anterior border. Umbos somewhat acute, approaching a central position, and separated from one another by a space in which a groove occurs for the ligament, which is partly external, partly internal (fig. 90). Short straight hinge-line, with a small ear on each side of umbos.

Fig. 90.—Hinge of *Lima*, showing cartilage-pit.

The following have been divided off as sub-genera:—

Radula.—Strong smooth radial ribs, with some concentric markings. Small byssal cleft under anterior ears.

Plagiostoma.—Smooth, or with very slight radial markings.

Ctenostreon.—A coarse form with strong irregularly moulded radial ribs, and a distinct anterior opening for the byssus.

Lima is an important genus, ranging from *Carboniferous* to *Recent.*

Pecten (fig 91).—Free, or attached only by byssus. Shell almost equilateral, slightly inequivalve, the right valve being

Fig. 91.—*Pecten* (*Chlamys*) *islandicus* (Post-Pliocene). Right valve, showing the byssal notch.

Fig. 92.—*Janira quinquecostata* (Cenomanian).

the more convex; form almost semicircular ventrally, the border becoming straighter towards the pointed umbos. Distinct ears on each side of umbos, the anterior being often the larger. Anterior ear of right valve sometimes deeply notched back for the exit of the byssus, as in the important sub-genus **Chlamys.** Radially ribbed, sometimes very delicately; but commonly on a bold but regular scale. A triangular cartilage-pit appears internally under each umbo.

The external shell-layer exhibits the prismatic structure with marked distinctness. Both layers are calcite (*Sorby*).

An abundant and important genus. *Devonian* to *Recent.*

Janira (fig. 92).—Inequivalve, the left valve flat or concave. Both valves with well marked ears, and ornamented with strong radial ribs.

Inner shell-layer often lost (*Zittel*) and probably aragonite.

Cretaceous to *Recent*, particularly the former.

Aviculopecten. — Ally of Pecten, but more inequilateral. Anterior ear small, posterior larger and broader. Radially striated. Cartilage in several grooves, which are fairly parallel to the hinge-line.

Devonian to *Permian.*

The next two genera, although monomyarian, possess hinge-teeth.

Plicatula (fig. 93).—Attached by Umbo of right valve. Form much like Ostrea. Umbos rather acute, but not prominent. Concentrically marked, and sometimes radially folded. Two divergent cardinal teeth in each valve, with a cartilage-pit between them.

Trias to *Recent*. Especially *Jurassic* and *Lower Cretaceous*.

Fig. 93.—*Plicatula spinosa* (Lias). Showing the teeth and cartilage-pit.

Spondylus.—Attached by right valve, not merely by the umbo. Form fairly regular, rounded ventrally, more acute dorsally, and almost equilateral. Umbos separated somewhat, with a small ear on either side. Right (lower) valve with a triangular space between the umbo and hinge-line, in which is a central groove which partly receives the cartilage. Radially ribbed; right valve sometimes with long spines. Two curved cardinal teeth in each valve, with the cartilage-pit between them.

The inner shell-layer is formed of aragonite, and is therefore easily destroyed and seldom found.

Jurassic to *Recent*. Abundant at the present day.

CHAPTER XXV.

FOSSIL GENERIC TYPES.

VIII. Scaphopoda.

The animals of this division are Marine, and are sometimes regarded as the lowest of the gastropods. The shell is tubular, and has often been mistaken for the calcareous case of a worm.

Dentalium.—Shell of varying size; tubular, slightly curved, and tapering from the wider anterior to the narrower posterior end. It thus resembles an elephant's tusk in form, but is open at both ends. Surface sometimes smooth, sometimes longitudinally striated.

Ordovician to *Recent*. Especially *Cainozoic*.

IX. Gastropoda.

These include the typical univalves. The shell is spirally coiled, except in such simple types as the Limpet, and the terms used in describing it are as follows :—

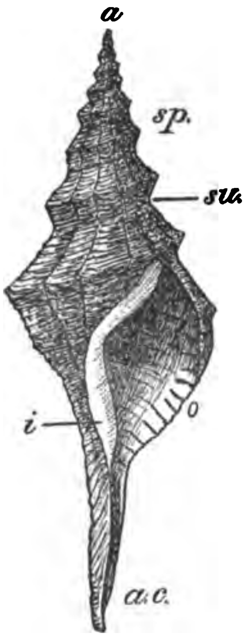


Fig. 94.—Gastropod (*Fusus*). *a*, Apex. *a.c*, Anterior Canal. *i*, Inner Lip. *o*, Outer Lip. *sp*, Spire. *su*, Suture.

Spire.—The coiled portion of the shell above the terminal and youngest whorl.

Whorl.—A single revolution of the spiral coil of the shell.

Suture.—The line of junction of successive whorls, as seen on the surface of the shell; commonly marked by a groove.

Umbilicus.—The hollow sometimes left in the centre of the shell when the whorls do not touch one another internally. This separation sometimes occurs only in the last whorl.

Columella.—The solid axis commonly formed where the whorls come in contact in the central line of the spire. This columella is often set with one or more ridges, winding spirally up it.

Apex.—The point from which the spire commenced its growth. In the old age of some gastropods partitions are formed within the shell below the apex, and the earliest part of the spire finally breaks away. The shell becomes thus imperfect, and is said to be *decollated.*

The apex forms the *posterior end* of the shell, the mouth the *anterior*.

Mouth.—The terminal opening, sometimes very broad, sometimes even slit-like. It is *entire* when in no way notched or prolonged into canals.

Canals.—Tubular folds of the shell at the mouth, often open along their under side. An *anterior canal* may occur, running out in front, and a *posterior*, directed up the outside of the spire,

Holostomatous shells have the mouth entire (fig. 101); *Siphono-*

stomatous shells possess an anterior canal. The animals of the latter division are, at the present day, almost all carnivorous.

Inner Lip.—The margin of the mouth nearest to the axis of the spire.

Outer Lip.—The margin of the mouth away from the axis of the spire. This margin is sometimes thin, sometimes thickened, sometimes prolonged into spines, the latter being in reality tubular folds resembling the canals.

Varices—Ridges or spinose bands running from the apex at intervals down the shell, and representing those stages in the growth of the spire when spines or thickenings of the outer lip took place (fig. 96).

Operculum.—A horny or calcareous plate borne by the posterior part of the foot of the animal in some genera, and serving to close the mouth of the shell when the animal retracts itself.

The spire is typically so coiled that, when the apex is placed above, and the mouth below and facing the observer, the mouth lies to the right of the axis. Such shells are *right-handed. Left-handed shells*, however, occur at times, in which the spire is coiled in the opposite direction.

The representation of gastropod shells in drawings with either the apex or the mouth upwards must be a matter of indifference, the best nomenclature of the extremities of the shell being, as already stated, "anterior" and "posterior," not "lower" and "upper."

Several terms have been used to describe the form of the shell as a whole. The following may require explanation:—

Turbinate.—Shell rather broadly conical as regards the spire, and approaching hemispherical below (fig. 103).

Turreted.—Shell with an elongated spire, and not much prolonged anteriorly (fig. 100).

Spindle-shaped.—Shell with the anterior end also produced and narrowed, so that the stoutest region lies between two tapering portions (fig. 94).

The shell-substance in most gastropods consists of three layers, as can be seen with a lens when the shell of modern examples has been cut across. In life, it is covered in very many genera by a skin, or "periostracum." The shell is formed of calcareous prisms as in the lamellibranchs, these prisms being grouped to form lamellæ which are arranged in the central layer differently from those of the outer and inner layers. See Zittel, *Palæontologie*, Bd. ii., p. 158; *Cambridge Nat. Hist.*, *Molluscs*, p. 255.

The material is aragonite, and hence gastropods are often represented in fossil deposits only by casts. Some few species (for the character is not even generic) have an outer layer com-

posed of calcite. Mr. P. F. Kendall regards the shell of Scalaria as calcite; and he remarks that the first two whorls in those species of Fusus which possess a calcite layer consist entirely of aragonite.*

The gastropoda mostly inhabit the sea. The fresh-water genera will be specially indicated. The division of the Pulmonata contains several genera that live entirely on land.

With the exception of the Pulmonata, all the gastropod genera, the shells of which are here discussed, belong to the order Prosobranchiata, or, in default of complete evidence, are placed in that order on account of the resemblance of their hard parts to those of living forms. The division of the members of this order into Holostomata and Siphonostomata, according to the character of the mouths of their shells, has proved unsatisfactory, since it separates forms otherwise closely allied. The genera are here taken practically in the order adopted by Fischer, a group of allied shells being occasionally marked out by inclusion between two black lines.

A. Prosobranchiata.

The animal has its branchiæ placed anteriorly to the heart.

Conus.—Spire short; last whorl large and narrowing anteriorly, so that the shell, with its apex upwards, resembles a short cone set on a steep inverted one. Mouth slit-like and long, with a slight anterior fold. Outer lip sharp, and notched back near the suture. Columella smooth. Surface commonly smooth, with mere growth-lines. S. P. Woodward quotes *Conus monilis* with a specific gravity of 2·910 (hence aragonite), and the fossil *Conus ponderosus* of the Miocene as 2·713. Some species may, therefore, contain a thick calcite layer.

Upper Cretaceous to *Recent*. Abundant at the present day.

Pleurotoma (fig. 95).—This genus has been greatly subdivided. Shell spindle-shaped; spire rather longer than the last whorl, and generally well indented at the suture. Mouth long, with anterior canal. Outer lip with a marked notch near the suture, which leaves a band on the shell as it closes over during growth. If the lip in a fossil form is broken away, the growth-lines may still indicate its backward curve. Columella smooth or with one or two ridges. Surface commonly ribbed vertically or horizontally, often with little spirally arranged knots.

* "Aragonite Shells in the Coralline Crag." *Geol. Mag.*, 1883, p. 499.

Cretaceous to *Recent.*

Voluta (fig. 96).—This name also covers many sub-genera. Shell thick. Shape somewhat like Conus, but more nodose and irregular. Spire fairly short; last whorl large. Mouth long,

Fig. 95.

Pleurotoma rotata (Post-Pliocene). Showing the notched outer lip.

Fig. 96.

Voluta athleta (Barton Beds). Showing knots and varices; also folds on the columella.

with slight anterior fold. Outer lip fairly thick. Columella and inner lip with several ridges. Surface often marked with prominent short spinose outgrowths, and sometimes with corresponding varices.

Upper Cretaceous to *Recent.* Especially *Eocene.*

Fusus (fig. 94).—Shell thick. Spindle-shaped to ovoid, typically the former. Spire fairly long. Mouth oval, with long straight anterior canal, and no posterior notch. Columella smooth. Some late Cainozoic species have an outer calcite layer (*Kendall*). The genus has been much subdivided.*

The sub-genus **Clavella** has its mouth sharply narrowed to form the canal, not tapering down as in Fusus proper.

Jurassic to *Recent.* Most abundant in earlier *Cainozoic.* Clavella is *Cainozoic*, especially *Eocene.*

Buccinum (the Whelk; fig. 97).—Shell fairly ovoid, with few whorls, the last being large. Spire, however, prominent. Mouth oval, with a broad shallow anterior fold representing the canal. Inner lip smooth. Surface generally marked with vertical and spiral ridges.

Pliocene to *Recent.*

Nassa.—Like Buccinum, but canal-fold more marked and slightly oblique. Outer lip marked with fine ribs running inwards.

Upper Cretaceous to *Recent.* Especially later *Cainozoic.*

* For a revision of many species, see Grabau, *Smithsonian Collections*, No. 1417 (1904).

Murex.—Shell thick, ovoid to spindle-shaped; whorls strongly convex. Mouth rounded, but prolonged into a well-marked and sometimes long anterior canal, the sides of which fold over so as to make it almost tubular. Outer lip thick, and sometimes ribbed. Surface set with three or more strong varices, which are often remarkably knotty or spinose. Outer layer of shell calcite (*Kendall*).

Upper Cretaceous to *Recent*.

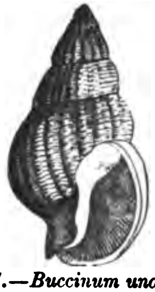


Fig. 97.—*Buccinum undatum* (Pliocene).

Fig. 98.—*Ficula reticulata* (Pliocene).

Trophon.—Ally of Murex. Spindle-shaped. Canal wider and bent on one side. Varices not set with knots.

Pliocene to *Recent*.

Purpura.—Shell thick, ovoid. Spire rather short. Mouth oval, with a canal-fold scarcely more marked than that of Buccinum. Inner lip flattened down and smooth. Outer layer of shell calcite (*Sorby*).

Miocene to *Recent*.

Cassidaria.—Shell thick and ovoid. Spire short; last whorl large and strongly convex. Mouth elongated oval, with a well-marked broad and obliquely bent canal. Outer lip expanded; inner lip often ridged. Surface variously marked.

U. Cretaceous to *Recent*.

Ficula (Pyrula in part; fig. 98).—Shell thin, ovoid, narrowed anteriorly. Spire very short, last whorl very large. Mouth large, and prolonged into a broad open anterior canal.

Lower Cretaceous to *Cainozoic;* especially later *Cainozoic*, but not abundant.

Rostellaria.—Spindle-shaped; spire long, commonly without much indentation at the suture. Mouth long, with a somewhat tubular elongated anterior canal, and a posterior groove-like canal running towards the apex of the spire. Outer lip rather broadly expanded and sometimes notched on edge.

In the sub-genus **Hippochrenes** (fig. 99) the shell is generally smooth. The posterior prolongation of the mouth runs up to the apex of the spire, and the outer lip is not serrated, except by the occurrence of a small anterior notch. In the sub-genus **Rimella** the surface is striated. The posterior groove is shorter, and the outer lip is thickened and sometimes serrated.

Cretaceous to *Recent*. Compare next two genera.

Alaria.—General outline spindle-shaped; spire fairly long. Mouth elongated, with well-marked anterior, but no posterior canal. Outer lip much expanded, and prolonged into finger-like canals. Surface often set with varices and knobs.

This genus is variously limited by different authors, and some of its species are often carried over into Aporrhais.

Jurassic to *Cretaceous*.

Aporrhais (Chenopus).—Distinguished from Alaria by the prolongation of the mouth posteriorly as a groove-like canal

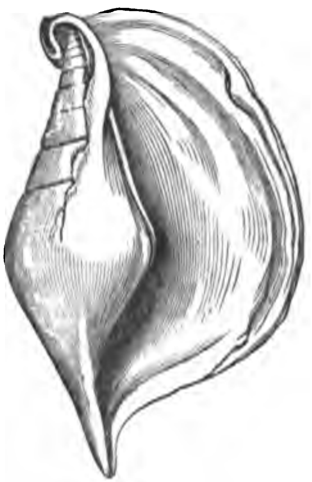


Fig. 99.—*Rostellaria* (*Hippochrenes*) *ampla* (London Clay).

Fig. 100.—*Cerithium plicatum* (left hand figure) and *Cerithium elegans* (Hamstead Beds). Showing the short oblique anterior canal.

part way up the spire. The anterior canal is shorter than is common in Alaria, and there is a shallow fold in the outer lip near it. From Rostellaria it is distinguished by the prominent finger-like processes of the outer lip.

Lias to *Recent*.

Cerithium (fig. 100).—A very typical turreted shell, the spire being elongated and conical, and the last whorl being in no way disproportionate in bulk. Mouth oval, obliquely sloped towards a well-marked and short anterior canal, which is somewhat bent aside and backwards. The mouth is often narrowed posteriorly so as to terminate in an acute angle. Surface often set with knots.

Trias to *Recent*. Especially *Cainozoic*.

Potamides.—Close ally of Cerithium, with straighter canal, which is commonly not so well marked. **Brackish and fresh-water.** Difficult to mark off from Cerithium except in its actual habitat. In life, Cerithium has no periostracum, while Potamides has a thick one.

Eocene to *Recent*.

Melania.—Much like Cerithium, but holostomatous. Form at times nearly ovoid. Apex sometimes worn away during life (decollated). **Fresh-water.**

Wealden to *Recent*.

Melanopsis.—Ovoid rather than turreted, with short spire. Mouth with anterior notch or small canal, and a more or less marked groove-like posterior prolongation. Inner lip thickened. Apex sometimes decollated. **Fresh-water.**

Cretaceous to *Recent*.

Turritella (fig. 101).—Shell as typically turreted as Cerithium. Spire long, often only slightly indented at the suture; at other times with convex whorls. Holostomatous; mouth oval to round, but sometimes narrowed anteriorly. Outer lip thin. Surface marked with spiral ribs or striæ, there being a striking absence of the knots and vertical ribs so common in Cerithium and Melania.

Jurassic to *Recent*, but conspicuously *Cainozoic*.

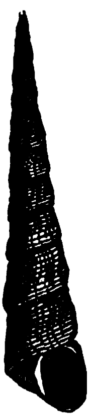


Fig. 101.—*Turritella incrassata* (Pliocene).

Pseudomelania (Chemnitzia in part).—Turreted; commonly large. Little indented at the suture, and hence fairly conical. Mouth oval, without canal; wider in front and narrowed behind. Surface commonly marked by fine growth-lines.

Trias to *Miocene*.

Bourguetia.—Shell large, turreted, and elongated. Whorls distinctly convex; longitudinally striated; last whorl large. Mouth round in front and narrowed behind.

Jurassic. Perhaps *Carboniferous.*

Nerinea (fig. 102).—Ally of Cerithium. Turreted; almost conical, commonly with a spiral band-like ridge above the suture. Mouth diamond-shaped to oval, with short oblique anterior canal. The outer and inner lip, as well as the columella, have commonly one or more ridge-like thickenings, which wind up inside the shell, so that sections parallel to the axis are very characteristic, the projection of these ridges into the cavity leaving only a remarkably constricted space for the animal. In some species (grouped under sub-genera) an umbilicus occurs in place of the columella, and distinctions are made according to the number and distribution of the thickenings on the different internal surfaces of the shell.

Jurassic to *Cretaceous.*

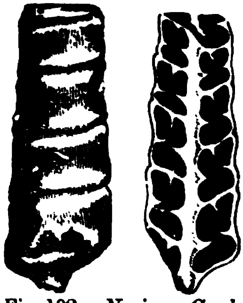


Fig. 102.—*Nerinea Goodhalli* (Corallian). Worn specimen, with section to show reduction of the internal cavity.

Rissoa.—Always small, about 5 mm. long. Shell thick; rather broadly conical; spire fairly long Mouth oval, rather narrowed posteriorly, with thickened outer lip. Surface often vertically ribbed.

The animal lives mostly near shore.

Jurassic to *Recent.* Especially *Cainozoic.*

Hydrobia.—Small, and much like Rissoa; typically rather longer in the spire. Surface smooth. Mostly **brackish** or **fresh-water.**

Jurassic to *Recent.* Especially *Cainozoic.*

Paludina (Vivipara).—Shell thin; turbinate; whorls strongly convex. Mouth oval to almost circular, slightly narrowed posteriorly. Sometimes an umbilicus is present. Surface smooth or with mere growth-lines. **Fresh-water.**

Jurassic to *Recent.*

Natica.—Shell thick; practically globular, the spire being very short, the last whorl very large and convex. Mouth semicircular (*i.e.*, straight-sided at the inner lip and curved along the outer) or approaching oval. Outer lip sharp; inner lip thickened. Umbilicus typically well marked, but in some species absent. Surface commonly smooth. Spiral operculum.

Trias to *Recent*. Some of the earlier forms described as Natica belong to Naticopsis.

Littorina (the Periwinkle).—Shell thick, almost globular, with few whorls, the last being large. Mouth rounded, more acute posteriorly. Outer lip sharp at the edge; inner lip flattened at the columella. Surface commonly marked with growth-lines and spiral striæ. Outer layer composed of calcite (*Sorby*). The animal inhabits the shore, sometimes forming considerable shell-banks.

Lias to *Recent*.

Nerita.—Shell thick. Spire very small; last whorl very large, and prolonged out rather more obliquely than in Natica, so that the total effect is not so globular. Mouth semicircular; outer lip commonly thickened and set with little ridges directed inwards; inner lip generally also ridged. Columella flattened. Surface smooth, or spirally ribbed.

Lias to *Recent*. Mostly *Cainozoic*. The Mesozoic forms have the typical shape, but most of them have smooth lips, the outer lip being, moreover, sharp in many examples.

Neritina.—Close ally of Nerita, the shape being similar. Outer lip sharp, not thickened; inner lip marked by ridges. Surface ornamented with coloured lines and spots, which are preserved even in many fossil specimens. Typically **fresh-water**; sometimes **brackish.**

The form of the shell and its mouth-characters will not serve to distinguish Neritina from some of the early Neritas, which are, however, undoubtedly marine.

Eocene to *Recent*. Perhaps *Mesozoic*.

Naticopsis.—Form like Natica, but expanding very rapidly. No umbilicus. Mouth approaching oval. Operculum convex outwardly, and not spiral.

Devonian to *Trias*.

Turbo.—Form typically turbinate, sometimes approaching Littorina. Mouth round, lips not meeting to form a continuous border, part of the mouth being bounded merely by the surface of the whorl. Surface of shell often spirally ribbed. Operculum thickened with calcareous deposit till it becomes outwardly almost hemispherical, the massive examples from large living species being sometimes used as ornaments. See Trochus.

Ordovician to *Recent*.

Trochus.—Allied to Turbo, but broadly conical, and somewhat flattened below. Mouth without continuous lips, but more angular than in Turbo. Operculum horny only. The genus has been much divided into sub-genera. Some fossil forms, the

opercula being absent, may possibly be referred to Turbo; but the difference of outer form is characteristic.

The living species are mostly shallow-water forms.

Gotlandian to *Recent.*

Phasianella.—Ally of Trochus. Shell like a rather elongated Paludina; often fairly large. Mouth oval; outer lip thin. Surface smooth.

Cretaceous to *Recent.* Earlier forms have now been referred to Bourguetia.

Euomphalus.—Shell fairly large. Almost discoidal, the spire being very low. Mouth more or less polygonal, with a slight notch not far from the suture. Umbilicus extremely wide. The earlier part of the shell is sometimes seen in sections to be cut off by partitions.

Gotlandian to *Carboniferous.*

Pleurotomaria.—Shell like Trochus, but sometimes with a low spire. Mouth fairly round; outer lip with a deep slit in it, which runs back along the whorl. As growth proceeds, this slit is closed over, and leaves a band-like mark or a ridge running spirally round the shell about the middle of the whorl. Umbilicus sometimes present. Surface of shell generally handsomely ornamented with spiral ribs and knobs; but no trace of these appears in casts, which are common in some formations and which are not identifiable with certainty.

Cambrian to *Recent.* Abundant in earlier *Mesozoic;* very rare at present day.

Murchisonia.—Shell turreted; slit in outer lip, as in Pleurotomaria, and similarly closed by a band as the shell grows. Surface smooth, or with longitudinal ridges.

Cambrian to *Trias;* especially *Devonian* and *Carboniferous.*

Bellerophon.—Formerly often classed as a Heteropod. Shell shaped like a rather open Nautilus, the spired character typical of the gastropods being wanting. Mouth widely expanded and fairly circular, the shell coiling over inwards symmetrically in the centre of its inner lip. Outer lip deeply notched, a corresponding band running round the exterior of the shell.

The shells are often distorted and compressed in the older formations, and the expanded character of the mouth becomes partly lost. Distinguish carefully from Cephalopods.

Cambrian to *Permian.*

Galerus (Calyptræa in part).—Shell rather like that of the

Limpet (Patella), being flatly conical; but generally with a trace of spiral winding at the apex. Below, a spirally bent plate, which is free anteriorly and is attached along its posterior margin, crosses what would otherwise be a wide unbroken mouth. The under side of the apex is thus partly partitioned off. In **Calyptræa** proper this plate is represented by a spoon-shaped or bent process dependent from below the apex.

Galerus is *Upper Cretaceous* to *Recent*.

Patella.—The Limpet. Shell like a flattish cone; mouth oval; apex of shell nearly central above it. Surface usually radially ribbed.

Cretaceous to *Recent*.

Note.—Shells allied to Patella occur in the oldest Cambrian strata; in the absence of the animal, it is difficult to refer shells of this type to existing genera.

B. Pulmonata.

The animal breathes by a lung-sac in place of branchiæ. The group is almost entirely fresh-water or terrestrial. Delabeche (*Geol. Observer*, 2nd. ed., p. 122) gives the specific gravity of land-shells as 2·82 to 2·87. The material is thus probably aragonite.

Helix (the common Snail; fig. 103).—Shell variously shaped, but commonly rather flatly conical; at times approaching dis-

Fig. 103.—*Helix occlusa* (Oligocene).

Fig. 104.—*Planorbis euomphalus* (Oligocene).

coidal. Mouth obliquely semicircular or oval; outer lip sometimes slightly expanded and thickened; inner lip represented, as in Turbo, partly by the surface of the whorl. Sometimes, however, a calcareous thickening occurs in the position of the inner lip (fig. 103). Rather broad umbilicus. Surface commonly smooth, with mere growth-lines. Terrestrial.

Eocene to *Recent*. Species very numerous at the present time. The fact that the animal lived on land may account for its apparent absence in earlier periods, sub-aerial deposits being rarely preserved.

Bulimus.—Elongated ovoid, or turreted, often of large size. Mouth oval, not oblique, and rather long from anterior to posterior end. Thickened and continuous lips, which are sometimes expanded. No umbilicus. Surface commonly smooth, or only slightly ornamented. **Terrestrial.** See note on Helix.

Upper Cretaceous to *Recent*.

Limnæa.—Shell particularly thin and fragile. Elongated oval, with large final whorl. Mouth large, rounded anteriorly, elongated from front to back. Lips thin and sharp. Columella twisted obliquely. Surface smooth. **Fresh-water.**

Purbeck to *Recent*. Especially *Cainozoic*.

Planorbis (fig. 104).—Shell delicate, as in Limnæa; various in form, but typically discoidal, the spire being very short, and the coils almost in one plane, as in Euomphalus. Mouth semicircular to oval. Outer lip sharp; inner lip represented by the surface of the whorl. Umbilicus very broad. Surface commonly smooth, with mere growth-lines. **Fresh-water.**

Jurassic to *Recent*. Especially *Cainozoic*.

X. Pteropoda.

While the small and commonly conical calcareous shells of several of the Thecosomata, or shell-bearing Pteropods, are found in Cainozoic deposits, some large Palæozoic genera occur, which differ widely from the modern type. Their reference to the Pteropods must still be considered provisional, since, in the face of such strange forms as Calceola among the Corals and the Hippuritidæ among the Lamellibranchs, these conical and sometimes operculate shells may belong to groups, the other members of which differ from them in external aspect. Mr. G. F. Matthew has, it may be noted, referred Hyolithes to the worms (*Trans. R. Soc. Canada*, vol. vii., 1901, sect. 4, p. 101).

Hyolithes (**Theca**).—Shell small or large, even reaching 20 cm.

in length. Triangular in cross-section; straight, tapering, forming a long steep pyramid. Aperture at the wider end of the shell, its border lying obliquely to the axis. An operculum has been observed fitting into it. Commonly marked with oblique striæ. These shells are often crushed flat in early Palæozoic shales, but the long pyramidal form remains recognisable.

L. Cambrian to *Permian*. Almost all are early Palæozoic.

Conularia.—Shaped like a straight steep-sided pyramid, as in Theca, and similarly variable in size. Some species are slightly curved at the posterior end. Four-sided, giving square, or approximately square, cross-sections. Each side bears a shallow longitudinal furrow. Commonly marked with oblique striæ.

Septa have been observed, dividing off the lower part of the cavity.

Cambrian to *Lias*. Almost all are early Palæozoic.

Tentaculites.—Often described as the tube of an annelid. Rather small, steeply conical; circular in cross-section. Surface marked with ring-like ridges, which lie in planes perpendicular to the axis of the shell. The forms with longitudinal striæ have a small ellipsoidal expansion at the initial end (*Novak*).

Ordovician to *Devonian*.

XI. Cephalopoda.

The shell-bearing forms of these highly developed molluscs were in former ages far more numerous than at the present day; and the species are often sufficiently constant and widely spread to serve in marking special palæontological zones. At the present time we have a prevalence of one great dibranchiate order (which includes the ordinary cuttle-fish, Argonauta, &c.), while the tetrabranchiate type (Nautilus) is decadent.

We must leave for zoologists the many interesting questions that have been raised in the last few years, and content ourselves with placing the common fossil remains discussed under the broad headings Nautiloidea, Ammonoidea, and Phragmophora, without question as to the dibranchiate or tetrabranchiate character of the animals that gave rise to them.

The shells are sometimes straight, sometimes coiled over at one or both ends, sometimes closely and spirally coiled throughout; but, with very few exceptions, the coiling, when it occurs, takes place in one plane, so that the distinction between these shells and the ordinary gastropod univalves is marked. The regular partitions (septa), by which the cephalopod shell is

divided internally, form another very distinctive character. The remains of cephalopods may occasionally be very bulky, and are certainly among the most familiar fossils.

Terms used in describing the hard parts :—

Involute shell.—The shell is coiled, but the later coils or whorls overlap and conceal the earlier, only the last, in many cases, being left externally visible (fig. 109).

Umbilicated shell.—The later coils touch but do not conceal the earlier, a more or less wide depression, the *umbilicus*, occurring thus on each side of the shell (fig. 108).

Evolute shell.—The coils do not touch one another, an open spiral being produced (*e.g.*, Crioceras).

Outer side.—The convex side of the whorl in coiled forms, often called *ventral*, the latter being a term unsafe to use in the absence of evidence as to the animal itself.

Keel.—A rib sometimes found running along the outer side of the whorl.

Inner side.—The concave side of the whorl in coiled forms, often called *dorsal*.

Posterior end.—The initial end.

Anterior end.—The end where the aperture occurs from which the animal protruded.

Siphuncle.—The siphonal tube, which contained the siphon of the animal, traversing and connecting the successive chambers of the shell. Its walls are often calcified, and it can be well seen in sections of the shell, or emerging on the surface of one of the septa.

Septa.—The partitions which are successively formed as the animal grows, cutting off the earlier part of the shell. They are typically concave towards the aperture of the shell, but are often greatly folded, particularly towards the edges (fig. 114). See Suture-line below.

Septal Neck.—The cup-like or funnel-like fold of the septum where the siphuncle passes through it. Sometimes the apex of this fold is directed anteriorly, sometimes posteriorly. Shells in which it is anterior are *Prosiphonate;* those in which it is posterior are *Retrosiphonate.* (See also Eastman, trans. of Zittel, 1900, p. 542.)

Suture-line.—The line along which the septum meets the wall of the shell. This is sometimes very sinuous, and may be well seen on slightly worn specimens (fig. 108).

Lobe.—A fold of the suture-line directed posteriorly (fig. 107).

Saddle.—A fold of the suture-line directed anteriorly (fig. 107).

Interseptal Chambers.—The interspaces between the septa.

Body-chamber.—The final cavity which was occupied by the animal at the time of its disease.

Mouth.—The terminal aperture of the shell. This is sometimes constricted (fig. 106) sometimes fully open, sometimes surrounded or flanked by remarkable expansions of the shell. The distance from the outer to the inner border of the mouth is termed its *height*.

Aptychus.—A calcareous body like an operculum (fig. 105), formed of two plates, which resemble in outline the valves of a lamellibranch. These plates are often found detached; but during the life of the cephalopod they were brought together along their straight edges and occupied a position near the mouth of the shell, probably closing it as an operculum. In some cases the two plates are permanently united (*Synaptychus*). It has been suggested that those forms in which an aptychus is unknown may have possessed the structure in a horny condition.

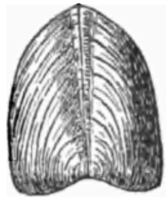


Fig. 105.—Aptychus of an Ammonite. Solenhofen Stone (Upper Jurassic), Bavaria.

Anaptychus.—A body resembling the aptychus, but formed of one plate only; found as thin dark lustrous impressions; probably a horny form of the operculum.

The shell-substance in cephalopods is aragonite, according to both Fuchs and Sorby. Mr. C. A. Schwarz (*Geol. Mag.*, 1894, p. 457) shows that fragments of Nautilus have a specific gravity of 2·68, whence he infers that the material is calcite. But a considerable amount of organic matter is set free when such fragments are dissolved in acid, and is perhaps responsible for the low figures obtained on examining modern Nautili. The Ammonites, in their present condition, consist of calcite, as also do their aptychi and the guards of Belemnites. The view that the original material of Ammonites was aragonite is supported by the fact that whole beds of aptychi are known from which the Ammonites have been dissolved away. An aptychus is sometimes found lying surrounded by a mere impression of the spiral shell. In any case, it is probable that some structural difference accounts for this difference in resisting power.

The ready destruction of the shell causes casts of cephalopods to be very common. The body-chamber, and many or all of the interseptal chambers, may become infilled with crystalline calcite; the body-chamber is, however, often filled up with mud. When the shell decays, the casts thus formed of the successive chambers generally cohere, and the form of the shell is retained. But sometimes the sutures have become represented only by curving interspaces, and the cast is divided up by them into detachable

blocks. The extreme folding of the sutures in the Ammonites may cause these separate casts of the chambers to remain interlocked with one another and yet to possess a certain amount of freedom, so that they can be moved about on one another when taken in the fingers.

Cephalopod shells are composed of two layers, the outer one more opaque, the inner lamellar, thicker, and nacreous. The septa appear to consist only of the nacreous layer.

All the cephalopoda are Marine.

A. Nautiloidea.

By analogy with the living Pearly Nautilus, the animals of the genera here placed are believed to have been tetrabranchiate, *i.e.*, to have possessed four branchiæ. The shell is not (as in some dibranchiates) included in the body of the animal. It is straight, curved, or coiled, with a mouth of various form. The septa are, in typical examples, very simply curved, concave towards the anterior side of the shell, and forming suture-lines with, at most, very simple lobes. The shell, with the exception of the rare genera Bathmoceras and Nothoceras, is retrosiphonate; and the siphuncle stands away from the bounding wall of the shell, piercing the septa sometimes in their centre.

The surface of the shell is only plainly ornamented, if at all.

Nautilus.—Shell coiled in one plane, involute, but sometimes with a small umbilicus. Mouth not contracted, commonly rather high. Body-chamber large. Suture-lines forming a simple curve, or only slightly lobed. Siphuncle almost central. Surface smooth; very rarely with grooves or ridges. (Example:—*Nautilus pompilius.*)

Trias to *Recent.* Nautilus is the only tetrabranchiate genus living at the present day.

Note.—The generic name "Nautilus" is now restricted as above. The older forms are widely umbilicated, and have often a perforation at the centre. **Barrandeoceras** (*Ordovician* and *Gotlandian*) and **Trocholites** (*Ordovician*) are especially interesting early representatives.

Discites.—Shell laterally compressed, with broad shallow umbilicus, all the whorls being exposed. Small perforation at centre. Whorls four-sided in cross-section, sometimes with a groove on outer side. Suture-line forming a very simple curve. Surface with mere transverse growth-lines or delicate longitudinal ribs. (Example:—*Discites mutabilis*).

Carboniferous.

Lituites.—Ally of Nautilus, but commencing with a small umbilicated (or even evolute) coil, and then continuing as a straight form, often of considerable length. Mouth often constricted, with a deep notch on the outer side. Siphuncle nearer inner side.

Ordovician and *Gotlandian.*

Orthoceras.—Shell straight like a long cone; commonly circular in cross-section. Mouth not contracted. Body-chamber long. Septa simply curved, concave forwards. Suture-lines unlobed, or at most with very feeble foldings. Siphuncle central, or nearer to the margin; simple in character, but sometimes expanded laterally in each chamber. Surface of shell smooth, or simply ribbed.

Cambrian to *Trias.* Most abundant in *Gotlandian.*

Actinoceras.—Shell at times very large; often referred to Orthoceras. Like Orthoceras; but the siphuncle (endosiphon) is included in another much larger tube, which is expanded between the septa, forming a series of oblate spheroids, and at times as wide as half the shell. Delicate canals radiate from the siphuncle to the outer tube, and open into the interseptal chambers. The outer tube is frequently contracted internally by the development of obstructions of calcareous and organic material, deposited on its inner wall; these eventually form an annular thickening, which greatly reduces the tube. These additions sometimes become dissolved away after the central tube has been infilled with mud; hence the primary wider hollow becomes restored, but a solid rod-like cast runs down its centre.

Cambrian to *Carboniferous.*

Gomphoceras (fig. 106).—Pear-shaped, the shell having a straight or nearly straight axis; it commences as a wide cone, and finally closes over towards the mouth. Mouth much constricted, forming merely a T-shaped slit, the upright line of which is regarded as ventral, the cross-piece being dorsal. Septa and sutures simply concave. Siphuncle as in Orthoceras, varying in position in different forms. Surface smooth, or only finely striated.

Fig. 106.—*Gomphoceras ellipticum* (Silurian), showing the constriction of the mouth.

Gotlandian. Perhaps *Ordovician;* the fusiform later types are

probably Poterioceras. (Foord, *Catalogue of Fossil Cephalopoda*, pt. i. p. 215.)

Poterioceras.—Shell smooth, slightly curved, inflated in middle portion, and then again contracted. Mouth elliptical, not contracted. Siphuncle nearer to convex side, and inflated between the septa. Septa oblique to axis of shell.

Ordovician to *Carboniferous*.

Cyrtoceras.—Shell like a curved and rather rapidly expanding Orthoceras. Cross-section generally oval. Mouth unconstricted. Septa and suture-lines simply concave. Siphuncle as in Orthoceras, but almost always near the convex side. Surface smooth in ordinary species, or only lightly striated.

Cambrian to *Permian*. Especially *Gotlandian*.

Phragmoceras.—Many of the species placed under this genus have been transferred to Gomphoceras, Poterioceras, &c. Phragmoceras proper is distinguished from Gomphoceras by the curved shell, which at times even shows a trace of evolute coiling; and from Cyrtoceras by the constricted and T-shaped mouth.

Ordovician and *Gotlandian*.

B. Ammonoidea.

The members of this group have often been closely connected with the Nautiloidea under the title of Tetrabranchiata. However, from the globular, and not conical, form of the initial chamber of the Ammonites (which resembles the first stage of the chambered body in Belemnites, Spirula, &c.) some zoologists place them as dibranchiates. The group attains its fullest development in the Mesozoic era, where it terminates.

Exceptions to the typical mode of coiling of the shell are probably rarer among the Ammonoidea than among the Nautiloidea. Straight or evolute turreted forms come in most numerously in the later Mesozoic deposits. The margin about the mouth differs from that of the Nautiloidea in very often bearing a broad or spine-like prolongation on the convex side, and sometimes ear-like processes on its lateral margins. No such remarkable constriction of the mouth occurs, however, as in Gomphoceras and its allies, the expanded processes in the Ammonites pointing fairly forwards. The body-chamber is on the whole larger than in the Nautiloidea; but it must be borne in mind that this final portion and the mouth of the shell, being unsupported by septa, are comparatively rarely preserved.

The suture-lines are typically more complex than in the

Nautiloidea, and the amount of folding increases from the first septum to the later ones. Considerable attention has been paid to the form of the suture-lines, and their common course is as follows (fig. 107):—A lobe, the *External lobe* (or "ventral lobe"), occurs on the convex side of the shell, and is sometimes divided into two by a small saddle (fig. 113). On either side of this lobe comes a saddle (the *External saddle*); then a lobe (the *first lateral lobe*); then the *first lateral saddle*, the *second lateral lobe*, the *second lateral saddle*, and perhaps still further lobes and saddles, which are styled *auxiliary*. On the concave side of the whorl, where the two halves of the suture-line again meet, there occurs an unpaired *Internal lobe*. The last auxiliary saddle, occurring just above this lobe, is sometimes called the *Internal saddle*.

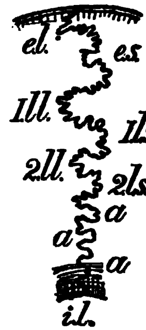


Fig. 107.—Suture-line of an Ammonite (*Harpoceras*). The mouth lies to the right. *e.l*, External lobe, bisected by a median saddle on the keel. *e.s*, External saddle. *1. ll*, 1st lateral lobe. *1. ls*, 1st lateral saddle. *2. ll*, 2nd lateral lobe. *2. ls*, 2nd lateral saddle. *a*, *a*, Auxiliary lobes and saddles. *i.l*, unseen Internal lobe.

The siphuncle of the ammonoids, with the exception of the one genus Clymenia, runs along the convex side of the shell. The group of the Ammonites is prosiphonate.*

The surface of the shell is often, and particularly in the later types, highly ornamented with ribs and knots, which are independent of the suture-lines (figs. 113 and 114), the latter being visible only upon worn specimens and casts. At times, as in Gault specimens from many localities, the inner and thicker nacreous layer is alone preserved, and the whole surface of the shell has a brilliant pearly iridescence.

Finally, the bodies known as aptychi (fig. 105) or anaptychi are found associated with so large a number of ammonoid genera that they form a further point of difference between this group and the Nautiloidea.

* Forms of Ammonite occur in which the earlier whorls are retrosiphonate; in one or two septa following on these the septal neck projects on both sides; and finally the shell becomes purely prosiphonate. But the broad classification of the Ammonoidea by the direction of the septal neck in adult forms seems well founded, since the older genera are so persistently retrosiphonate, while those of Mesozoic times are prosiphonate.

Sub-group 1—RETROSIPHONATE SHELLS WITH SIPHUNCLE ON THE CONCAVE SIDE.

Clymenia (fig. 108).—Shell spiral, broadly umbilicated; cross-section of whorl oval, flattened laterally. Mouth notched on either side. Suture-lines usually with only one lateral lobe, which is simply curved or angular. Siphuncle in contact with the concave side of the whorl. Retrosiphonate. Surface smooth; rarely ribbed.

Exclusively *Devonian*.

Sub-group 2—RETROSIPHONATE SHELLS WITH SIPHUNCLE ON THE CONVEX SIDE.—This sub-group includes all the shells known as **Goniatites**.

The shells are very variously coiled, being at times involute, at times widely umbilicated. Cross-section of whorl may be flattened laterally, or broad (fig. 109), or fairly oval. The whole shell is thus sometimes discoidal, or sometimes almost globular

Fig. 108.—*Clymenia undulata* (Devonian). Showing suture-lines where the shell has been worn away, with a single angular lobe.

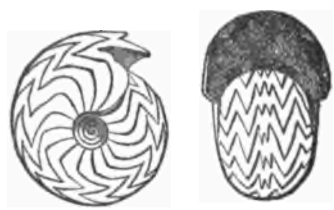


Fig. 109.—*Glyphioceras mutabile* (Carboniferous). Showing suture-lines.

through the strong convexity and the involute arrangement of its whorls. The suture-lines are occasionally slightly folded, but are commonly zigzag or bent rather sharply, the lobes and saddles being sometimes numerous. The lobes and saddles are, however, not subdivided by notched or foliaceous boundaries, as occurs in the next sub-group (fig. 112). The siphuncle is in contact with the convex side of the whorl, and is best seen where it emerges through any septum which may be displayed terminally on the specimen. Retrosiphonate. Aptychi have been recorded.

Glyphioceras (fig. 109).—Shell involute, generally globose. Suture-line with external lobe divided by a small median saddle; external saddle narrow; lateral lobe pointed; lateral saddle broad and rounded. Surface practically smooth. (Examples:—*Glyphioceras crenistria*, *Gl. sphæricum*, *Gl. truncatum.*)
Carboniferous and *Permian*.

Gastrioceras.—Shell with wide umbilicus. Suture-line with broad and deep external lobe, with small median saddle; first lateral lobe deep and angular; second lateral lobe small and angular. Surface with longitudinal striæ; often with transverse ribs in addition, which are nodose near inner ends. (Example:—*Gastrioceras Listeri.*)
Carboniferous and *Permian*.

Prolecanites.—Shell with wide umbilicus; whorls flattened laterally. Suture-line with several deep lobes and saddles, the lobes broadly pointed at the ends, the saddles rounded at the ends and narrowed near their bases. Surface smooth. (Example:—*Prolecanites compressus.*)
Devonian and *Carboniferous*.

Note.—**Bactrites** (*Ordovician* to *Carboniferous*) is the straight form of the Goniatites. **Pronorites** (*Permo-Carboniferous*), with its accessory serrations at the ends of the lobes, and **Medlicottia** (also *Permo-Carboniferous*), with its still more elaborate suture-lines, link the Goniatites completely to the sub-group of the Ammonites.

Sub-Group 3—PROSIPHONATE SHELLS WITH SIPHUNCLE ON THE CONVEX SIDE.—These are the successors of the Goniatites, and are distinguished, apart from the character of their septal necks, by a greater complexity in the suture-lines, the main lobes and saddles being variously subdivided and broken up (fig. 112). The mouth-border is produced, not notched, on the outer side. The surface of the shell is also more strongly ornamented than in the preceding sub-groups, and is, indeed, very rarely smooth.

This sub-group covers the great series of shells which are commonly styled **Ammonites**, the earliest forms of which are now known from the Coal-Measures of Texas.* It has become necessary to subdivide the old genus of "cornua Ammonis," and to establish a large number of new ones, each example of which may be properly styled an "Ammonite." Fischer's restriction of "Ammonites" to the members of the newer genus Arietites seems liable to cause confusion, and would destroy

* J. P. Smith on the "Super-family" Arcestidæ, in Monograph xlii. (1903), *U.S. Geol. Survey*.

the utility of the word "Ammonite," which now, as formerly, covers a great series of shells allied to one another.

New subdivisions are being, however, continually introduced, and for details larger and special works must be consulted.

Ceratites.—Shell umbilicated; cross-section of whorl somewhat flattened laterally. Suture-lines sometimes with auxiliary lobes and saddles. The saddles are always rounded, the curve approaching semicircular; but the lobes are subdivided, their posterior border being zigzag* (fig. 110). Surface marked with

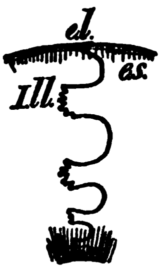


Fig. 110.—Suture-line of *Ceratites nodosus.* *e.l*, External lobe (which is broad when viewed from above). *e.s*, External saddle. *1. ll*, 1st lateral lobe.

Fig. 111. — Natural cast of *Arcestes Bœckhi* (Trias), showing traces of successive constrictions. Part of the shell remains on the left, and the suture line can be traced on the right-hand portion of the cast. (After Mojsisovics.)

ribs, which do not pass on to the outer border, but which often bear knobs as they approach it.

Exclusively *Triassic.*

Trachyceras.—Shell with rather narrow umbilicus. Sutures like Ceratites in the earliest species; but in later forms both the saddles and the lobes are denticulated (*i.e.*, bent into a zigzag form). Surface ribbed transversely, the ribs set with knots; a furrow runs along the convex margin. (Example:—*Trachyceras Aon.*)

Trias.

Arcestes (fig. 111).—Shell involute, sometimes with small

* A very similar type of suture recurs among Cretaceous Ammonites referred to the family of the Amaltheidæ.

umbilicus; whorls markedly convex. Mouth slightly reduced by the folding over of its outer and lateral borders. Body-chamber occupying more than a whole whorl. Sutures with numerous auxiliary lobes and saddles, the line being complex and foliaceous, so that the markings look like the outlines of little branching trees. The axis of each lobe and saddle is, however, straight. Surface smooth, or with fine transverse striations.

The mouth-border appears to have become thickened internally at various stages of growth, so that casts (fig. 111) exhibit well marked and rather wavy grooves running at wide intervals from the outer to the inner side of the whorl. (Example:—*Arcestes subumbilicatus.*)

Trias. Also *Permo-Carboniferous* of India, with another genus of Ammonite, **Cyclolobus.**

Monophyllites.—Shell rather flat and discoidal, with fairly wide umbilicus. The whorls enlarge rather rapidly, giving a high mouth. Suture-lines with numerous lobes and saddles, which are foliaceous; but each saddle terminates anteriorly in a

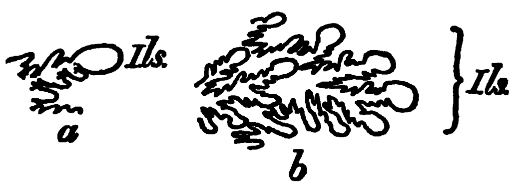


Fig. 112.—*a*, First lateral saddle of *Monophyllites Simonyi*. *b*, First lateral saddles of two adjacent septa of *Phylloceras heterophyllum*, showing the extremely foliaceous character of the suture-lines.

single oval leaf-like form, although its sides are subdivided into leaflets (fig. 112, *a*). Surface smooth, or with fine slightly curving striæ. (Example:—*Monophyllites Simonyi.*)

Trias.

Phylloceras.—Shell rather flat; involute, or with very small umbilicus. Mouth high. Numerous lobes and saddles, steadily increasing in size outwards, the saddles being broken up into leaf-like foldings with rounded terminations, the lobes into sharper notches (fig. 112, *b*). Surface smooth, or simply striated; no keel. Here and there external or internal thickenings of the mouth-border may be formed, producing in the former case ridges

on the surface, or in the latter case constrictions, evidence of which occurs on casts of the interior, as in Arcestes (fig. 111). (Example :—*Phylloceras heterophyllum.*)

Lias to *U. Cretaceous.*

Amaltheus.—Partly involute. Form rather discoidal, and sometimes flattish. Mouth high, its border being produced into a long process on the outer side. Body-chamber occupying only two-thirds of the last whorl. Suture-lines markedly folded; several auxiliary lobes and saddles present. Surface smooth or variously ribbed; a distinct median ridge or keel runs along the convex side, and is often knotty, or obliquely grooved, so as to resemble a piece of rope. (Example :—*Amaltheus margaritatus.*)

Trias and *Jurassic.*

Oxynoticeras.—Form much like Amaltheus. Two or more auxiliary lobes are present on each side, but the lobes and saddles are broad, and the whole suture-line is less strongly foliaceous than in Amaltheus. Surface smooth, or marked with rather delicate curving ribs. (Example :—*Oxynoticeras oxynotus.*)

Lias to *Lower Cretaceous.*

Schlœnbachia.—Form like a thick Amaltheus, with a smooth keel. Suture-lines with only one auxiliary lobe, *i.e.*, three lobes in all on each side; lobes and saddles consequently broad. The lobes are fairly simple, and at times even approach the Ceratites type (fig. 110). Surface with strong curved ribs; keel often prolonged into a horn. (Example :—*Schlœnbachia inflata.*)

Cretaceous.

Ægoceras (fig. 113).—Shell with wide or narrow umbilicus; cross-section of whorl fairly circular. Body-chamber occupying rather less than one whorl. Suture-lines foliaceous, with few auxiliary lobes; lobes and saddles rapidly diminishing in size. Internal lobe bifurcating at end. Surface with fairly straight simple ribs, which cross the outer side of the whorls, there being no keel. In some exceptional cases, these ribs bifurcate near the outer side of the whorl (compare Schlotheimia). Ægoceras and its allies are thus among the most simply marked ammonites. An anaptychus occasionally occurs in this genus. (Example :—*Ægoceras capricornus.*)

Lias.

Schlotheimia.—Sometimes regarded as a sub-genus of its close ally, Ægoceras. Like Ægoceras, but surface with strong ribs,

which often bifurcate, and which are directed anteriorly when they reach the outer side of the whorl, so as to form on the convex border a series of V-shaped ridges. The ribs from opposite sides, however, die away just before they actually meet, so that the apex of the fold is wanting. (Example:—*Schlotheimia angulata.*)

Lower Lias.

Psiloceras.—Also closely allied to Ægoceras, and sometimes included in that genus. Resembles Ægoceras, but surface sometimes smooth, sometimes with simple ribs that do not traverse

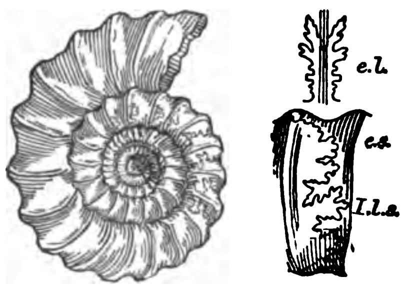


Fig. 113.—*Ægoceras capricornus* (Middle Lias), with portions showing suture-line enlarged. *e.l*, External lobe, with small median saddle and trace of siphuncle, viewed from above. *e.s*, External saddle. *I.l.s.*, 1st lateral saddle, which is distinctly smaller.

the outer side of the whorl. A slight keel occasionally occurs. (Example:—*Psiloceras planorbis.*)

Rhætic and *Lower Lias.*

Arietites.—Form much like Ægoceras, but with no approach to an involute character. Suture-lines much folded, with only one auxiliary lobe. Surface with plain or (rarely) somewhat nodose ribs, which are sometimes bent sharply forward above. Plain median keel, on either side of which is a furrow. Fischer employs the name Ammonites, given by Lamarck, exclusively for this genus. (Example:—*Arietites Bucklandi.*)

Lower Lias.

Harpoceras.—Shell rather discoidal; umbilicus sometimes wide, sometimes narrow. Mouth-border furnished with a spinose prolongation of the keel, and with lateral ears. Body-chamber occupying about two-thirds of the last whorl. Suture-lines with auxiliary lobes, but not particularly foliaceous (fig. 107). Internal lobe not bifurcating at the end (compare Ægoceras). Sur-

face marked with striations or ribs, which at first curve forward on leaving the inner side of the whorl, and then backward, finally again bending forward at the outer side of the whorl. The markings are thus sickle-shaped; but this character is much more emphatic in some species than in others. A smooth keel is present, occasionally with a shallow furrow on each side.

An aptychus formed of two plates has been found. (Example:—*Harpoceras serpentinum.*)

Jurassic, commencing in *Middle Lias.*

This next and important series of forms, including the family of the Stephanoceratidæ, is characterised by the absence of a keel.

Stephanoceras (fig. 114).—Form thick, with fairly wide umbilicus; cross-section of whorl broad and rounded, not high. Mouth eared in fairly young forms, and sometimes contracted by folding over of the lateral processes. Suture-lines with few lobes and saddles, but markedly foliaceous. Internal lobe not divided at its apex. Surface with fairly straight ribs, which bifurcate or split still further as they near the outer side of the whorl, over which they run continuously (fig. 114). Nodose ornamentation occurs sometimes where the ribs divide. An aptychus of two plates is known. (Example:—*Stephanoceras humphriesianum.*)

Jurassic.

Fig. 114.—*Stephanoceras modiolare* (U. Jurassic). Viewed from the front, showing the broad section of the whorl, the shell having been broken away until a septum, with its folded surface, has become visible. The trace of the siphuncle is seen externally; and this example also illustrates the lack of connexion between the suture-lines and the surface-ornamentation.

Holcostephanus.—Close ally of Stephanoceras. Ribs united in groups on inner side of whorl, and running continuously over convex side. Mouth sometimes constricted, as in Perisphinctes. (Example:—*Holcostephanus astierianus.*)

U. Jurassic and *Cretaceous.*

Cœloceras.—Widely umbilicated; cross-section of whorl typically narrower than in Stephanoceras. Mouth not eared. Internal lobe of suture-line divided into two at its apex. Surface marked as in Stephanoceras; but plain ribs are often intercalated between the others. Compare Perisphinctes. (Example:—*Cœloceras commune.*)

Middle and *Upper Lias.*

Cosmoceras.—Umbilicated; cross-section rather oval, the mouth being typically higher than in Stephanoceras, and furnished with long lateral ears. Surface-markings as in Stephanoceras, but ribs rather more curved and nodose; a row of spines or knobs is formed on each side of the outer median line of the whorl, the median area itself being smooth. (Example:—*Cosmoceras Jason.*)

Middle Jurassic to *Neocomian.*

Parkinsonia.—Form rather flat; umbilicus wide. Mouth high rather than broad, with lateral ears. Surface with fairly straight ribs, which mostly bifurcate near the outer margin of the whorl, but which are broken by a median external furrow. (Example:—*Parkinsonia Parkinsoni.*)

Middle Jurassic.

Perisphinctes.—Form like Parkinsonia. Mouth eared in young forms. Suture-lines with a deep foliaceous lobe following on the second lateral lobe, which is small. Surface-markings much like Parkinsonia, but ribs sometimes dividing into three or four branches, and no median furrow. The formation of a slightly constricted area behind the mouth-border at various periods of the animal's growth leaves here and there its traces upon the outer surface of the shell in the form of a smooth depressed ring running round the whorl. (Example:—*Perisphinctes Tiziani.*)

Jurassic to *Neocomian.*

Hoplites.—Form somewhat discoidal, with narrow umbilicus, and at times approaching involute. Mouth high. Suture-lines delicately notched, and with several auxiliary lobes. Surface-markings much like Stephanoceras, but the ribs are more wavy, and nodose processes are common on them, near either the umbilicus or the margin. Moreover, there is in many species a well-marked median furrow down the outer side of the whorl. The lateral compression of the shell also distinguishes it from Stephanoceras, which is stout. (Example:—*Hoplites lautus.*)

Tithonian and *Cretaceous.*

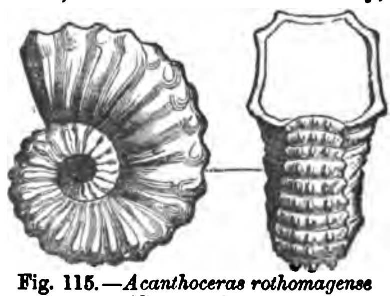


Fig. 115.—*Acanthoceras rothomagense* (Cenomanian).

Acanthoceras (fig. 115).—Umbilicated; whorls strongly convex, cross-section broad and commonly well rounded. Suture-lines

with broad and not markedly foliaceous lobes and saddles. Surface with straight ribs, not bifurcating, which sometimes cross the outer side of the whorl, but which sometimes are interrupted by a shallow furrow. These well marked ribs are generally set with numerous knobs. (Example :—*Acanthoceras rothomagense.*)

Cretaceous. Mostly *Albian* and *Cenomanian.*

Lytoceras.—Widely umbilicated; whorls distinctly convex. Suture-lines delicately foliaceous, the lobes and saddles divided into symmetrical halves by an anterior or posterior fold of the line respectively (compare fig. 116). Often no auxiliary lobes and saddles. Surface of shell simply marked with fine ribs, and almost smooth. Casts are sometimes ringed round with constrictions which indicate occasional thickenings of the mouth-border (see fig. 111). (Example :—*Lytoceras jurense.*)

Lias to *Cretaceous.*

Finally there remains a number of Ammonoidea distinguished by abnormalities of form. In the classification generally adopted, the genera Hamites, Turrilites, and Baculites are placed near Lytoceras, on account of the symmetrical subdivision of some one or more of their lobes and saddles (fig. 116). Similarly, Crioceras, Ancyloceras, and Scaphites are allied to Acanthoceras.

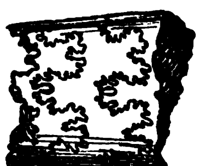


Fig. 116.—Portion of *Baculites anceps* (U. Cretaceous), the siphonal side being upwards; showing the bilateral subdivision of the lobes and saddles. The mouth lies towards the right.

Baculites (fig. 116).—Shell straight, narrowing to a point posteriorly, and laterally compressed. Aptychus known.

Cretaceous.

Hamites.—Evolute. Shell straight for part of its length, but curved over in a hook-like manner at one or both ends, so as to bend back parallel to its former direction. Hamites is sometimes restricted to forms which have bent thus twice or three times during their growth, while those only once bent are styled Hamulina. Surface of most species rather simply ribbed.

Cretaceous.

Crioceras.—Form like an Ammonite, but evolute. Surface variously marked; but generally with strong simple ribs. See Ancyloceras.

Jurassic to *L. Cretaceous.*

Ancyloceras.—Form commencing like Crioceras; then becoming straight; and finally curving back along its inner side like the terminal part of Hamites. Hence Ancyloceras may be a late stage in the growth of Crioceras.

Jurassic to *Lower Cretaceous.*

Scaphites (fig. 117).—Form commencing as an involute shell; then running straight for a short distance; and finally curving back along its inner side. Commonly much stouter and more rotund than Ancyloceras. Aptychus or synaptychus known.

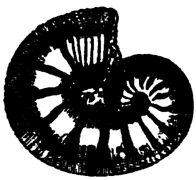


Fig. 117. — *Scaphites æqualis* (Cenomanian).

Upper Cretaceous.

Turrilites.—Form spiral, generally left-handed (*i.e.*, opposite to the mode of coiling of typical gastropods). The whorls are sometimes not in contact. Surface commonly marked with nodose ribs. The suture-lines of course readily distinguish this form from turreted gastropods; the cross-fracture of imperfect specimens has generally taken place along a septum, the characteristic ammonoid folding of which can at once be seen.

Cretaceous.

C. Phragmophora.

All are regarded as dibranchiate.

Belemnites (fig. 118).—The chambered shell in this genus is reduced to a conical body, the *Phragmocone* (or *Phragmacone*), which is divided internally by simple concave septa. The interseptal chambers are connected by a siphuncle, which runs down one side of the phragmocone, this being consequently called the *ventral side.* The phragmocone is closely fitted into a hollow, styled the *Alveolus,** which occurs at the anterior end of a strong pencil-like calcareous body, the *Guard* or *Rostrum.* This solid guard forms the object so commonly found, and is thus popularly known as the "belemnite."

* The Phragmocone itself has also been styled the Alveolus.

The guard is of various proportions, sometimes delicately tapering, sometimes broad and stout, sometimes thickening anteriorly for a certain distance and then decreasing in diameter, to expand again as the alveolus is neared. In cross-section, as when broken, it shows a fibrous radial structure, and the calcite of which it is formed is usually stained somewhat brown. The apex of the conical alveolus is directed slightly to the "ventral" side, and determines the point from which the calcite prisms radiate in the guard; hence the axis of the guard is eccentric, and the "dorsal" or "ventral" side of imperfect specimens can be determined by noting which part of the circumference is respectively farthest from or nearest to the point from which the prisms radiate.

Fig. 118.—Guard of *Belemnites*, cut open above to show remains of the phragmocone resting in the alveolus.

The guard has typically a smooth surface, on which vascular impressions, like those of ramifying rootlets, can occasionally be seen. A furrow sometimes runs down the ventral side, or more rarely down the dorsal, often reaching to the point of the guard. At the point itself furrows sometimes arise, extending some distance up the sides; and a common feature is the presence of two long and almost parallel grooves running thus up the dorsal side.

The alveolus is often empty; and sometimes the phragmocone is found without the guard. In fine and carefully cleaned specimens, not only can the phragmocone be seen in place, but traces of a broad expansion of its dorsal side extend considerably above and beyond it. This thin anterior expansion is the *Pro-ostracum*, and covers the ink-bag, the solidified contents of which, forming a black pear-shaped body, have also been found *in situ*. Above this, again, impressions of the crown of arms about the head of the animal may be seen, the little hooked teeth with which they were set lying in rows along them. Hence the "belemnite" familiar to collectors formed only the posterior hard part of an animal allied to our modern unprotected cuttle-fish.

Rhætic to *Albian*.

Belemnitella (fig. 119).—This form is practically only a subgenus of Belemnites, characterised by a slit at the anterior end of the guard and parallel to its axis. This slit reaches in to the alveolus, and marks the ventral side. The phragmocone (of which several specimens, mostly preserved in silica, are known), has a low ridge running down the dorsal side, a corresponding shallow groove occurring in the alveolus. The phragmocone, though rare, was described by Count Münster as early as 1830. The guard shows distinct vascular markings on its ventral surface. (Compare Actinocamax.)

Fig. 119.—Guard of *Belemnitella mucronata* (Senonian). Showing the slit and traces of vascular markings.

Fig. 120.—Guard of *Actinocamax plenus* (*Belemnitella plena*). Cenomanian.

Upper Cretaceous.

Actinocamax (1823; = **Attractilites**, 1807).—No alveolus, or only a shallow one, which is often four-sided rather than circular in cross-section (*Actinocamax quadratus*). The common character of these forms is the distinctly lamellar structure of the anterior end of the guard, so that it easily becomes broken away and injured. In apparently perfect specimens, however, as in *Actinocamax plenus* (fig. 120; often styled *Belemnitella plena*), the anterior end may be pyramidal, not hollowed out by an alveolus; in this case the phragmocone must have been surrounded by only a horny continuation of the guard. In the species quoted, a slight groove occurs at the apex, which may correspond to the slit in Belemnitella.

Both in Belemnitella and Actinocamax the guard may be suddenly reduced in diameter near its point, thus terminating in a short spinose process, the "mucro." It has often been suggested that Actinocamax is only an imperfectly preserved

Belemnitella; but the uniform character of specimens at certain horizons is evidence that the phragmocone was largely above, and not included in, the true calcareous guard.*

Upper Cretaceous.

Note.—Phragmophora with greatly elongated guards occur in the *Upper Trias.* In **Belemnoteuthis** of the *Oxfordian*, on the other hand, the guard is a mere short sheath about the phragmocone.

Belosepia of the *Eocene* has a short stout bent guard, expanded anteriorly, and protecting a curved phragmocone, a wide depression on the concave side of which does duty for a siphuncle. The pro-ostracum is large.

In **Spirulirostra** (*Miocene*) the guard forms a stout short process below a curved phragmocone, which possesses a true siphuncle. In the modern **Spirula** the phragmocone alone remains, in the form of a delicate evolute spiral shell, with a siphuncle on the concave side. This shell, though exposed by a cleft of the mantle, is truly internal.

Sepia (*Eocene* to *Recent*) has the merest trace of a guard at the end of a phragmocone, the chambers of which are flattened, and which forms the well-known "cuttle-bone." It is important to note, however, that cephalopods with a mere thin horny pro-ostracum (the "pen") over the ink-bag, and no trace of chambered shell or guard, occur as contemporaries of even the earlier belemnites. Thus **Geoteuthis** of the British *Lias* has been placed in the same group, the Chondrophora, as Loligo, the Squid of the present day.

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* As to Belemnitella and Actinocamax, see Dr. Cl. Schlüter, "Cephalopoden der oberen deutschen Kreide," *Palæontographica*, vol xxiv. (1876-7), p. 63, and plate lii. (17), &c.

CHAPTER XXVI.

FOSSIL GENERIC TYPES.

XII. Echinodermata.

THE Echinoderms present in their hard parts a great variety of forms, characterised, however, by the prevalence of petagonal symmetry. The fact that their shells or skeletons, external or internal, are built up of plates, causes their remains often to be found only in a fragmentary condition. The calcite of which these parts is composed assumes a completely crystalline structure: so that any part of the shell or skeleton cleaves across on fracture along the rhombohedral surfaces so familiar in Iceland-spar. The opaque white but gleaming cleavage-surfaces of echinodermal fragments may thus be picked out by the eye on rock-exposures from among the fractured remains of other organisms. The individual plates or block-like calcareous bodies of which the hard parts are composed are styled the *Ossicles*.

All the Echinodermata are Marine.

A. CRINOIDEA.

These are the typical "sea-lilies" or "encrinites." The animal during the whole or earlier part of its existence is fixed to the sea-bottom, commonly by a flexible stalk or *Stem*, which bears root-like processes at its base. The principal terms used in describing the hard parts of Crinoids are as follows :—

Ossicles or *plates*.—The individual calcareous bodies of which any of the hard structures are built up.

Calyx.—The cup-like structure, sometimes closed over above, formed of calcareous plates, and enclosing the body of the animal. Its under surface or *base*, which is attached to the apex of the stem (or, as in Holopus, directly to the sea-floor), corresponds to the upper surface of most echinoderms; its upper or *oral* surface bears the mouth and generally the anal aperture. The calyx and the arms are often spoken of together as the *Crown* of the crinoid, and the calyx is sometimes freely termed the "head."

The upper (ventral) covering, or *tegmen*, of the calyx may be membranous, with little plates developed in it, thus leaving a circular gap in fossil forms; or it may form a dome-like structure of numerous plates in contact. There is no doubt that in some genera this *dome* was represented by a flexible *ventral sac*.

The *Mouth* lies centrally on or below the tegmen, and grooves lead to it from the bases of the arms.

The *Anus* is typically excentric, and is interradial in position (see below); that is, it occurs between two of the arms. In some extinct genera, the dome bears one aperture, that of the anus, which then occurs almost centrally, and at times on the end of a tube or "proboscis." In these cases the mouth is concealed beneath the dome, and the brachial grooves run through the wall, and are prolonged as little canals towards the centre, where they reach the mouth.

The plates composing the calyx are grouped in several series from the base upwards to the region of the mouth. The lowest plates, meeting in the centre of the base, are 2 to 5 in number (commonly 5), and are termed *Basals*. They are often hidden in fossil specimens by adhesion to the upper stem-joints.

Sometimes, however, the base is formed of two cycles of plates, an upper one, the true Basals, in this case sometimes styled *Parabasals;* and a lower cycle, alternating with the upper, and termed *Infrabasals* (see fig. 122).

Next above the basals or the parabasals, and in either case alternating with them when the base has petagonal symmetry, is the cycle of the *Radials*, commonly 5 in number; vertically above these the arms of the crinoid rise. On each plate of this primary radial series one or more similar plates may stand (fig. 121), so that each arm may be supported on a vertical row of several ossicles, which are commonly entitled first, second, third, &c., radials (see "Arms" below). In several important genera these radial series are in contact laterally; but in other types there are plates or groups of plates intercalated between them, such plates being styled *Interradials*. In relation to the calyx as a whole, however, the basals or the parabasals are also "interradial" in position; the infrabasals, when present, are "radial" (see fig. 122).

Anal Interradial Group.—This group commonly contains more plates than the others, and, on its continuation over the oral surface of the calyx, bears the anus. Frequently, interradials are found in no other portion of the calyx.

Arms.—The ossicles composing these are all styled *Brachials*. Dr. P. H. Carpenter * regards the members of the radial series

* "Anatomical Nomenclature of Echinoderms," *Ann. and Mag. of Nat. Hist.*, 6th ser., vol. vi. (1890), p. 15; F. A. Bather, "British Fossil Crinoids," *ibid.*, vol. v., p. 313; and "Suggested Terms in Crinoid Morphology," *ibid.*, vol. ix., p. 51. See also the terminology in Wachsmuth and Springer, "Revision of the Palæocrinoidea," *Proc. Acad. Nat. Sci. Philadelphia*, 1879 (pub. 1880), p. 249. Also Bather, *Geol. Mag.*, 1898, p. 318.

above the first radial as all belonging to the arms. The lower cycles of his brachials thus correspond to the old second and higher cycles of radials; these Dr. Carpenter styles *Costals* (fig. 121). Any interradials between these thus become styled *Interbrachials*. Above the costals the arm often bifurcates, further dichotomous division taking place in many genera. The free stems and branches of the arms are sometimes formed of one vertical row of ossicles ("uniserial;" fig. 122), sometimes of two in contact, the ossicles alternating in the two rows ("biserial;" fig. 121).

On the inner surface of the arms a groove leads down from their tips to the upper part of the calyx.

Pinnules.—Small arm-like processes, also formed of calcareous ossicles, set in many genera on both sides of the grooves that run down the arms. In living crinoids these bear the reproductive elements.

The *Stem* is composed of a row of ossicles, placed vertically on one another, their articulating surfaces being variously ribbed and grooved. A central canal runs down through them all.

The Crinoidea form a considerable portion of some limestones, the scattered ossicles of their stems, with their circular cross-sections and often radial markings, having given rise to the name "entrochal marble." The abundance of stems at some horizons, apart from crowns, has often been remarked on, and it has been suggested that certain genera (as Actinocrinus) possessed the power of casting off their stems at particular stages of their growth. On the other hand, it has been pointed out that calyxes, unless at once filled with mud on the death of the animal, run much greater risk of destruction than the more solid stems, the ossicles of the calyx being scattered too widely for easy recognition.

While, on the whole, the more modern types of crinoids are marked out by the smallness of the calyx in proportion to the arms, by a general absence of interradials, and also of a prominent ventral sac or dome, yet the division of the group into "Neocrinoidea" and "Palæocrinoidea" can be no longer maintained. At the present time the classifications of specialists in this refined branch of palæontology cannot be regarded as having reached even a resting stage; consequently the genera here selected, while showing an interesting range of structure, are not placed under any system of subdivisions.

Encrinus (fig. 121).—Calyx rather shallow; 5 small infrabasals and 5 large parabasals present, the former generally

hidden by traces of the stem; 5 radial series composed of three cycles, the ossicles of the two upper cycles being now regarded by most authors as belonging to the arms (first order of brachials, styled costals). From these arise simply bifurcating arms, which have pinnules, and which are commonly formed of two rows of ossicles (an exceptional feature in a Neozoic form). Upper surface of the calyx solidly roofed over. Stem long; its ossicles are radially grooved on their articulating surfaces.

Trias.

Pentacrinus.—Calyx very small in proportion to the arms; 5 basals (sometimes 5 infrabasals and 5 parabasals); 5 radials, above each of which lie 2 ossicles (radials or costals). The arms are formed of one row of ossicles, and bifurcate again and again, with long and abundant pinnules. Stem long, with numerous little jointed lateral processes; in cross-section it is sometimes rounded, but commonly appears like a five-rayed star, the indentations between the rays being deep or shallow. The articulating surfaces of the ossicles of the stem always bear a pattern of five oval markings, which radiate symmetrically from the central canal. These stem-ossicles form very familiar fossils.

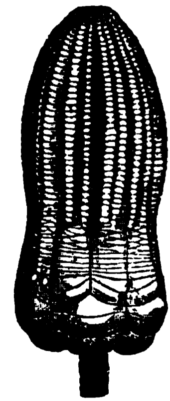

Fig. 121.—*Encrinus liliiformis* (Muschelkalk). The infrabasals and parabasals lie almost horizontally, and are invisible. Above these are seen the radials, each supporting two costals. The arms bifurcate, and ultimately become biserial.

Trias to *Recent*. Common in the *Lias*.

Apiocrinus.—Calyx narrowing slightly above; its plates, including the interradials, are fitted into one another to form a solid wall. 5 basals, alternating with which are the 5 radials, each bearing two large costals (2nd and 3rd radials); the basals rest on a circular plate, perhaps formed by the union of five infrabasals. Below this plate the stem commences, at first equal in diameter to the calyx, then contracting, and then becoming very gradually wider towards its rooted base. Hence above the narrowest part of the stem rises an egg-shaped or pear-shaped body, the upper half of which is the true calyx, the lower half being formed by the highest ossicles of the stem. Stem circular in cross-section. The arms are formed of a single row of ossicles,

and bear pinnules. They bifurcate only once or twice. Ventral sac known.

Lias to *Lower Cretaceous.*

Actinocrinus.—Calyx, including its dome, rather ovoid; 3 basals, 5 radials, with 2 costals (2nd and 3rd radials) above each; interradials (interbrachials) present, with more numerous plates in the anal group. The upper surface of the calyx is formed by a fairly high convex dome of plates, sometimes bearing near the apex an anal tube. Arms repeatedly divided; composed of two rows of ossicles, and arising from five protuberances at the base of the dome, so as to appear to emerge about midway between the apex and base of the ovoid "head." Stem round, the central canal appearing five-rayed in cross-section.

Gotlandian to *Carboniferous;* especially the latter.

Platycrinus.—Calyx formed of 3 basals, 5 fairly tall and vertical radials, 5 much smaller costals, and one interradial (or, rather, interbrachial) in each interspace between the arms; there may be, however, 3 plates in the anal series. Calyx roofed over as in Actinocrinus, with or without anal tube. Arms repeatedly bifurcating, composed at first of one row of ossicles, and later of two. Stem-ossicles often elliptical in cross-section.

Gotlandian to *Carboniferous;* especially the latter.

Ichthyocrinus.—Calyx formed of 3 small infrabasals (sometimes not visible on ext rior), 5 small parabasals, and 5 radials. 2 to 3 cycles of costals. Usually no interradials. Arms numerous, uniserial, and forming at their base a seemingly solid structure with the calyx. No pinnules known.

Gotlandian to *Carboniferous.*

Fig. 122.—*Cyathocrinus* (Gotlandian). Showing infrabasals, parabasals, and radials. Uniserial arms.

Cyathocrinus (fig. 122).—Calyx cup-like; 5 infrabasals; 5 large parabasals, forming part of the side-wall of the calyx; 5 radials; interradial plates occur only in the anal area. Upper surface with a greatly elongated and probably flexible dome. Arms long and repeatedly bifurcated, composed of one row of ossicles; no pinnules. Stem round.

Gotlandian to *Permian;* especially the former.

Heterocrinus.—Calyx small, somewhat cylindrical. 5 minute infrabasals, at times seemingly absent; 5 parabasals; 5 radials, with 2 costals above each. One or more of the radials is formed of two plates, united by a horizontal suture. Interradials in the

anal group, and prolonged upwards as a ridge. Ventral sac known. Arms long, uniserial, with strong pinnules. Stem pentagonal.
Ordovician.

B. Blastoidea.

In these forms, entirely Palæozoic and extinct, the calyx frequently resembles a closed flower-bud, having no free arms, an ovoid contour, and only a short stem. Running from the summit of the calyx down its sides are five elongated areas, the *ambulacral* (or *pseudo-ambulacral*) *areas*, which remind the observer of the well-known ambulacral areas on an echinoid. These are commonly seen as depressions, leaf-like in shape, or at times straight-sided. Specimens have been found in which the areas still bear pinnules, thus resembling crinoid-arms turned back and down over the calyx. A row of pores occurs down each side of the ambulacral areas, these openings being in reality interspaces between little lateral plates. The pores communicate with delicate canals, a bundle of which, called a *hydro-spire*, runs up internally on either side of the median line of the area, and opens at the summit of the calyx. Here there are usually five openings (*spiracles*), each representing two series of canals from adjacent ambulacral areas. The *mouth* is central, and the *anus* lies between the two posterior spiracles. An anal proboscis has been seen. The calyx is mainly composed of five plates (arising from a basal cycle), each of which is deeply notched above to receive the downward turned apex of an ambulacral area. These plates may therefore be regarded as *radials*.

Pentremites.—Calyx bud-shaped, narrower above; radials large. Ambulacral areas rarely reaching to the base. Short round stem.
Gotlandian to *Carboniferous;* especially the latter.

Granatocrinus.—Calyx resembling Pentremites; but the ambulacral areas extend down to the base, and the radials are small, the five upper plates (interradials) between them being large.
Carboniferous. The common "*Pentremites*" *ellipticus* thus becomes referred to Granatocrinus.

C. Cystidea.

In this group, the Cystideans, there is a spherical or ovoid calyx, sometimes with pinnulated lateral ambulacral grooves

resembling the areas in the Blastoids. These grooves, however, are often very narrow and small; they radiate from the *mouth*, which is apical. Two to thirteen short simple arms are occasionally also present; a short stem occurs in some genera.

A lateral aperture, and sometimes even two, may be found on some part of the calyx. Each is covered by a pyramid, the *valvular pyramid*, formed of little triangular plates.

The plates of the calyx are numerous and irregularly arranged. Some or all bear, in typical examples, minute pores, which are grouped in pairs, the members of each pair being united by a canal. In some genera these pores occur near the margins of the plates, and the pairs are made up of opposite pores on adjacent plates. Taking any one line of junction of two plates, the pores on each plate are then arranged along two sides of a triangle, the base of which is the line of junction; hence they include a rhomboid area, half of which lies on each plate. Across these areas striæ can be seen, which have caused authors to term them the *pectinated rhombs;* these markings are the traces of the canals by which the pores are connected. The pores are usually closed at their outer ends by a thin layer of the plate which bears them. The function of this system is unknown.

A larger number of genera can be referred to the Cystideans than to the Blastoids; but all these are also Palæozoic.

Echinosphærites.—Calyx spherical, with only rudiments of ambulacral grooves round the mouth, which has a raised border. A small opening occurs near the mouth, and is sometimes covered by a valvular pyramid. A third aperture, covered by a pyramid, is also present at some little distance from the mouth. Fixed by the base only; no stem. Bases of arms have been found attached to the rim around the mouth.

All the plates form pectinated rhombs at their lines of junction. *Ordovician.*

D. Echinoidea.

This group includes the common "sea-urchins," the spheroidal shells or "tests" of which are familiar objects, though ordinarily found denuded of their spines. They are never attached by a stem, and move about freely by means of little tube-feet protruded through certain of the calcareous plates of the test. The relative positions of the anal and oral apertures, and the arrangement of the organs of locomotion, form important points in their classification.

Test.—The shell, built up of calcite plates in contact with one another, by which the animal is surrounded.

Oral aperture.—An opening in the base of the test, fairly circular, within which the true mouth occurred during life. This aperture is reduced in living animals by a membrane or series of little plates, in the centre of which the mouth itself opens. The beautiful masticatory structure known as the "Lantern of Aristotle," though it falls away into the hollow of the test after death, and is commonly lost piece-meal through the apertures, has been found on careful cleaning in many fossil genera.

Auriculæ.—Calcareous arches or plates rising internally from the border of the oral aperture. They are five in number and symmetrically arranged, serving for the attachment of muscles which thrust forward the five-toothed "lantern." They may frequently be seen in fossils if the detrital matter that commonly fills the test is cleaned out from the mouth-aperture to a little depth. They together form the *Perignathic girdle.*

Anal aperture.—This appears as a second fairly large and circular opening, often diametrically opposite to that of the mouth. In life it was also reduced by a membrane bearing accessory plates, in which the anus itself occurred.

Apex of the test.—The highest point of the test when the flatter side, on which the mouth-aperture occurs, is placed below and horizontally.

Ambulacral areas.—Five areas, each composed of two rows of plates perforated by pores, which radiate from the upper part of the test. When these extend over the sides, and down to the oral aperture, as simple bands, they are said to be *perfect;* when the plates bearing distinct and regularly grouped pores terminate on the sides of the test, their representatives lower down having only indistinct or no perforations, the ambulacral area is described as *imperfect.* The *pores* are grouped in pairs towards the outer margin of the area, each plate thus bearing two pores. In many forms, through the intercalation of new plates above at the apex, the lateral ones become disarranged and finally united, so that compound plates arise bearing several pairs of pores. In *petaloid* areas the lines formed by the pores on the surface of the test converge and completely enclose the efficient ambulacral area, which thus becomes like an elongated simple leaf. In other cases the imperfect area is "open" below, the lines of pores not converging, but simply dying out. It may be remembered that each pair of pores represents one of the little "tube-feet" of the living animal.

Interambulacral areas.—Between the ambulacral series of plates lie five interambulacral series, each also typically composed of two rows of plates, which are larger and consequently less numerous than the ambulacral plates against which they abut on either side. Only in the early types of echinoids has the test more or less than 20 rows of plates, and in almost all these cases it is the interambulacral series that varies.

Apical Disc.—A series of plates at the apex of the test, and surrounding the anal aperture when this is apical. Each ambulacral area terminates here in a plate which bears a minute perforation, once connected with a sense-organ. Between these five *ocular plates* are five *genital plates*, larger and generally with a larger aperture. One of these genital plates is perforated, however, over all its surface, in addition to the principal aperture, and forms the *madreporic plate* or *tubercle*, which admits water into the stone-canal of the animal.

The genital plates are thus interambulacral, and the madreporic plate lies just to the right of the anterior ambulacral area. Thus, even in forms where the mouth is central and the anus is not posterior, but apical, the madreporic plate will serve to indicate the anterior portion of the test.

In the sub-group of the "Irregulares," the posterior genital plate is often absent.

Accessory plates may occur in the apical disc when the anus is not included in it; and sometimes the "disc" ceases to be disc-like, the three anterior ambulacral areas (or *trivium*) meeting in advance of the two posterior (or *bivium*), the connexion being maintained by a group of smaller plates (fig. 123).

The plates of the test may be ornamented with *tubercles*, large or minute. The principal ones, which may be handsomely developed, as in Cidaris, bear the spines, and have sometimes in their apex a circular pit, which does not perforate the test, but which causes them to be termed "perforate" or "imperforate." The beak-like appendages called "pedicellariæ" are in living forms found attached to the smaller granulations.

The *Spines* may be small and easily broken up, but in some genera are massive and even longer than the diameter of the test. Their rhombohedral calcite cleavage makes them difficult to extract entire. They are commonly found detached from the tubercles, on which they are jointed and held by ligaments during life. A common mode of ornamentation of the spines consists of granulated or serrated little ridges running longitudinally down them.

Lastly, to form any conception of the true characters of the

echinoid test, study must be made of recent examples, when it will be seen how the great mass of spines conceals the features (ambulacral grooves, tubercles, &c.) by which the palæontologist is accustomed to define his genera. A practical illustrative specimen may be prepared by selecting a modern Spatangus and rubbing off the spines lightly with the finger from one half of the test, leaving the other covered. Two of the petaloid ambulacral areas and half of the anterior one will thus be exposed, and will serve to explain the appearances seen in fossil examples.*

Sub-group 1—REGULARES.—In these echinoids the five ambulacral and the five interambulacral areas are each composed of two rows of plates, making twenty rows in all. The ambulacra are perfect, and therefore never petaloid. The oral aperture is in the centre of the base, aud the anal aperture is at the apex, and is thus included in the apical disc.

Echinus.—Test hemispherical and thin-walled. Tubercles similar on both kinds of areas, and all fairly small and simple. Ambulacral plates formed by the union of three primary plates, and hence each bearing three pairs of pores, which are grouped across the plate, not vertically under one another. Hence three bands, each formed of a series of pairs of pores, run up each margin of the ambulacral areas (p. 382). Spines small and simple in form.

Cretaceous to *Recent.*

Cyphosoma.—Test circular in horizontal section; flattened above and below. Tubercles with radial notches on the base, but without apical pit ("imperforate"); the principal and large ones form two rows on each of the ten areas of the test. From this cause, and in width, the two kinds of area much resemble one another. Ambulacral plates compound; but the pairs of pores form a single band, except near the apex and the mouth. Apical disc generally lost, the upper aperture being consequently large, and the test, as found fossil, almost annular (compare Cidaris). Spines long.

Jurassic to *Eocene.* But almost entirely *Upper Cretaceous.*

Acrosalenia.—Test small; form depressed spheroidal. Interambulacra rather larger than the ambulacra, both kinds of areas bearing two rows of "perforated" tubercles with radially notched bases. Pairs of pores forming only one row on each ambulacral margin. The interambulacral tubercles are the larger. A distinguishing point is the intercalation of several firm plates in

* For an important revision of the Echinoidea, see P. M. Duncan, *Journ. Linn. Soc.*, Zoology, vol. xxiii. (1890). p. 1.

the central area of the apical disc, whereby the anal aperture becomes thrust to the posterior side. Border of mouth-aperture notched. Spines rather thin.

Lias to *Lower Cretaceous.*

Cidaris.—Test fairly large; form flattened spheroidal, not perceptibly conical towards the apex. Ambulacral areas very narrow, forming wavy curving bands, with only a single row of pairs of pores on each margin. Commonly two small tubercles on each ambulacral plate. Interambulacra wide, with boldly developed tubercles, which are commonly "perforated," and are sometimes notched at the base. Apical disc commonly lost, a large aperture, like that of the mouth, being left (compare Cyphosoma). Spines thick, massive, of very various form, long or short, species of Cidaris having been named from these peculiarities.

Permian to *Recent*, diminishing throughout the Cainozoic systems.

Sub-Group 2—IRREGULARES.—In this sub-group the radial symmetry that prevails, except in minute details of the apical disc, throughout the sub-group of the Regulares, gives place to a distinctly bilateral symmetry, the plane of symmetry passing through the oral and anal apertures, the anterior ambulacral area and the apex. The anus is not included in the apical disc, and occurs sometimes even on the basal surface. The apical disc shows irregularities, the posterior genital plate being often absent. The oral aperture itself may be excentric. There are, as in the Regulares, only 20 rows of plates in all; but the pore-bearing parts of the ambulacral series frequently form petaloid areas.

Echinoconus (Galerites).—Conical; flat at base, which has an outline approaching pentagonal. Oral aperture in centre of base, without masticatory apparatus; anal aperture also on the base, but close to the posterior margin. Tubercles "perforate," minute, and numerous over all the test. Ambulacral areas perfect, narrow, the pairs of pores forming single marginal rows except on the base, where they become crowded so as to form three rows on each side. The posterior genital plate is imperforate. Spines small, rarely seen.

Cretaceous.

Discoidea. — Hemispherical, sometimes flattish; base flat. Apertures as in Galerites. Tubercles "perforate," small. Ambulacra perfect, narrow, with only one row of pairs of pores on each margin. Posterior genital plate imperforate in most species.

The essential character is the occurrence of ten low ridges radiating on the interior of the base from the oral aperture to the lateral walls of the test, and leaving corresponding grooves on casts.

Cretaceous.

Pygaster.—Depressed hemispheroidal, with flat base, which is roundly pentagonal in outline. Oral aperture central; anal aperture large and on upper surface, behind the apex, being narrower at its anterior and broader at its posterior end. Tubercles small, "perforate." Ambulacral areas much as in Discoidea. Posterior genital plate absent.

Jurassic to *Cretaceous;* also one *Recent* species.

Scutella.—This is an example of the extremely discoidal and flattened echinoids prevalent in some Cainozoic deposits. Base flat; upper surface only slightly convex; internal space much reduced. Posterior margin straight, or with a central notch. As the test grows, an indentation on its edge may increase in importance, until at last the test re-unites on either side of it, leaving it as a perforation. This remarkable feature is paralleled by Pygope among the brachiopods. Mouth central; anus small, and on the posterior margin. Tubercles minute. Ambulacra petaloid. Posterior genital plate absent.

Oligocene and *Miocene.*

The next six genera, like Galerites, were unprovided with a masticatory apparatus.

Echinobrissus.—Form approaching hemispherical, but rather depressed; base slightly concave, with an almost straight border between the two posterior ambulacra. Tubercles small. Oral aperture slightly in advance of the centre; anal on the upper surface, just behind the apex, and lying in a groove that widens posteriorly. Ambulacra imperfect, with nearly parallel sides, open below; outer pore of each pair elongated and slit-like. The posterior genital plate is imperforate.

Jurassic to *Recent;* characteristically *Middle Mesozoic.*

Clypeus.—Close ally of Echinobrissus. Test large, flattened. Tubercles small. Apertures as in Echinobrissus; but anal groove sometimes wanting. Ambulacral areas rather broad, imperfect, open below, but contracting near the base. Outer pore of each pair long and slit-like. Apex slightly posterior; posterior genital plate imperforate; madreporic plate central in the apical disc, while the posterior ocular plates are extended so as to reach the anal area.

Jurassic.

Collyrites (fig. 123).—Test ovoid, with rather flattened base. Tubercles minute. Oral aperture rather in front of the centre; anal aperture on posterior lateral surface. The striking character lies in the extension of the apical disc and its accessory plates, so as to form an elongated band running along the line of symmetry; hence the three anterior ambulacra (styled the "trivium") become divided from the other two (the "bivium"), which enclose on the posterior surface an area around the anus. Ambulacra narrow and perfect.

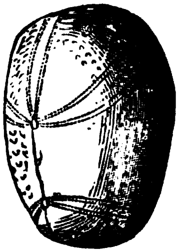

Fig. 123. — *Collyrites bicordata* (Coralline Oolite). Showing the separation of the ambulacra at the apex.

Jurassic and *Lower Cretaceous.*

Echinocorys (Ananchytes).—Test convex above, with rather vertical sides; oval in horizontal section; base flat. Tubercles minute. Oral aperture near the anterior margin; anal aperture near the posterior margin, and also within the base. Ambulacral areas fairly wide; perfect. Posterior genital plate absent.

Upper Cretaceous.

Holaster.—Form heart-shaped, *i.e.*, oval when viewed from above, with a broad notch anteriorly and a sharper posterior termination. Upper surface convex; base flat. Tubercles small. Oral aperture near anterior margin; anal aperture on the posterior lateral surface. Ambulacra perfect (compare Micraster, which has a similar form); the anterior ambulacral area lies in a well-marked groove, which continues round to the mouth-aperture. Posterior genital plate absent.

Cretaceous.

Micraster.—Form much like Holaster; typically heart-shaped; sometimes more acute, sometimes slightly truncated, at the posterior end. Tubercles small. Apertures as in Holaster; the test projects forward from behind the mouth-aperture so as to form a short covering below it. Pore-bearing areas set in grooves, the paired ones petaloid; the three anterior areas are longer than the posterior. An anterior groove, in which the unpaired ambulacrum lies, runs from apex to mouth as in Holaster. Posterior genital plate absent.

Upper Cretaceous to *Miocene.*

Note.—**Spatangus**, a *Cainozoic* and common living form, resembles Micraster, but has larger interambulacral tubercles on the upper surface, while the anterior unpaired ambulacrum is only feebly represented in its groove.

Sub-group 3 — PALÆECHINOIDEA. — The remains of early echinoids are rare, and the various genera have been collected by Zittel into this division, to which he opposes the "Euechinoidea," sub-divided into Regulares and Irregulares. Some Palæechinoids seem to have had tests with plates that moved slightly on one another, so that the whole could be deformed by pressure without fracture, as is the case in the exceptional living euechinoids, Asthenosoma and Phormosoma. Moreover, their most striking characteristic is a deviation from the normal number of twenty rows of plates.

Thus **Palæechinus** (*Gotlandian* to *Carboniferous*) is a spherical form with five normal and perfect ambulacral areas; but the interambulacrals are wide, and each is formed of five to nine rows of plates.

Archæocidaris, again, of the *Carboniferous* and *Permian*, has fair-sized tubercles on the interambulacra, and wavy narrow ambulacra, suggesting those of Cidaris; but there are from four to eight rows of plates in each interambulacral area.

Melonites, also *Carboniferous*, has several supernumerary rows of plates in both the ambulacral and the interambulacral areas.

Bothriocidaris (*Ordovician* and *Gotlandian*) has normal ambulacral areas, but only one row in each interambulacral area.

E. ASTEROIDEA.

The members of this group are of less assistance to the geologist than is the great group of the Echinoids, owing to the ease with which their hard parts become separated and dispersed. Passing over the allied Ophiuroidea, in which the long arms contain no prolongations of the viscera, we may note that the arms of the Asteroidea, or true Star-fishes, contain numerous skeletal ossicles, which give them at times considerable solidity. There are thus the little *ambulacral ossicles*, which, by meeting in pairs so as to form a ridge, cover the ambulacral vessel that runs down the under side of each arm. Beneath this ridge, and thus in the groove formed by it, the tube-feet of the star-fish lie during life. At the lateral margins of each arm are often two rows of *marginal ossicles*, one above and one below, each pair in contact. These ossicles are typically convex outwardly, often ornamented with granules or spines, and flat-sided where they abut against their neighbours, whether of the same or the adjoining row. At the base of the ambulacral ossicles a row of *adambulacral ossicles* always occurs. Accessory plates may be formed on the back of the arms, or between the marginals and the

adambulacrals. The marginal ossicles are not unfrequently found in fossil deposits.

Palæaster.—Form like the common Star-fish (Asterias or Asteracanthion), with deep ambulacral grooves. The ambulacral ossicles, unlike any modern form, are alternate, not opposite, on the two sides of the groove. Marginal and dorsal ossicles present.

Cambrian to *Carboniferous*.

Protaster of the *Gotlandian* and *Carboniferous* is an Ophiuroid.

Astropecten. — Form like the common Star-fish, but with strongly developed marginal ossicles.

Lias to *Recent*.

Goniaster.—In this type the form closely approximates to a pentagonal disc, through the extreme shortness of the arms; the notch between one arm and the next is represented merely by a shallow concavity, along which marginal ossicles form a firm border. Between these ossicles and the small ambulacral areas, with their adambulacral and ambulacral ossicles, are abundant accessory plates, thus covering five intervening triangular areas. The dorsal surface is also covered with accessory plates. This genus is consequently represented by fairly coherent specimens.

Jurassic to *Recent*. Fairly common in the *Cretaceous*.

XIII. Annelida.

The division of the Annelida is largely represented by the borings of marine genera in sands, which have become converted into cylindrical casts by the deposition of material during subsequent rising of the tide. Sometimes the infilling, as in the very early examples in the quartzites above the Torridon Sandstone, is conspicuous by consisting of a sand either more or less ferruginous than that into which the animal bored. If this infilling becomes consolidated more firmly than its surroundings, the cross-sections of the casts may stand out on weathered surfaces of the rock as little circular discs.*

The specimens of such borings from Sutherland and Ross-shire, as above described, and from the quartzite of the Wrekin ridge, may claim to be among the very oldest fossil remains.

The tube-building worms naturally leave abundant traces.

* For figures and descriptions of such objects see Sir J. W. Dawson, *Quart. Journ. Geol. Soc.*, 1890, p. 595.

Thus **Serpula** has a calcareous tube, often irregularly corrugated on the surface, and very variously curved; the tube commonly appears as if creeping forward in the fashion of a moving worm. It is usually fixed to other bodies, being thus often seen, for example, on the tests of Chalk echinoids. Common from the *Jurassic* to the present day.

Ditrupa forms an unattached simply curved tube, open at both ends, which closely resembles the scaphopod Dentalium. From this it may sometimes be distinguished by irregularity of curvature, and by being ornamented only on the side that was uppermost during life (*Zittel*).

Cretaceous to *Recent*.

CHAPTER XXVII.

FOSSIL GENERIC TYPES.

XIV. Arthropoda.

From a stratigraphical point of view, the Arthropoda become less important in Cainozoic deposits than they are in the Palæozoic, and hence the earlier types of Crustacea or "Arachno-Crustacea," which are often grouped together in the heterogeneous division of the Entomostraca, must claim our chief attention. Their common character is a variable number of body-segments (*Somites*), coupled with a simple type of organisation.

A. Ostracoda.

These little crustaceans have never more than 7 pairs of limbs, and are enclosed in a bivalve *Shell*, which corresponds to the shield formed by the union of the segments of the head and thorax in the Malacostraca. This shell is kept closed by a muscle. Its surface is smooth or variously marked, often with hemispherical knobs, and its small oval form is characteristic. The valves of ostracods are seldom liable to be confused with those of young lamellibranchiata (see fig. 124). The shell is chitinous or calcareous.

Hinge-border.—The line of junction of the two valves along which they remain united. Little teeth sometimes occur upon the hinge (fig. 124, *c*).

Ventral border.—The lower border, towards which the limbs of the ostracod are directed during life.

Eye-spot.—A fairly hemispherical tubercle occurring in some genera on the anterior part of the valve, and indicating the position of an eye.

The Ostracods are mostly Marine; fresh or brackish water forms will be specially indicated.*

Cypris (fig. 124, *a*).—Shell small, partly horny, and thin. Left valve the larger. Oval, or rather bean-shaped; ventral border commonly somewhat concave. No teeth. Surface generally smooth, and pierced with minute holes. Fresh-water.

Purbeck to *Recent.*

a

b

c

Fig. 124.—*a*, *Cypris purbeckensis* (Lower Purbeck Beds). The left valve is towards the observer. *b*, *Cypridea punctata*, var: *gibbosa* (Middle Purbeck). Left valve. *c*, *Cythere retirugata*, var: *rugulata* (Lower Purbeck). Interior of left valve, showing an anterior socket for the tooth of the right valve; then a tooth, followed by a bar-like ridge, which terminates in a posterior socket for the posterior tooth of the right valve. (The three figures after Prof. Rupert Jones.)

Fig. 125.—*Beyrichia* (Ordovician).

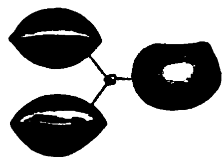

Fig. 126.—*Leperditia inflata* (Carboniferous). Natural size shown in centre.

Cypridea (fig. 124, *b*). — Like Cypris, but shell bearing a little beak-like process, with a notch behind it, at the anterior end of the ventral border. These are the common "Cyprids" of the Weald. Fresh-water.

Purbeck to *Wealden.*

Cypridina. — Shell small, thin, horny or calcareous. Oval, with a prolongation near the middle of the anterior border, beneath which a notch occurs.

* For interesting descriptions and figures of Purbeck and Wealden forms see T. Rupert Jones, *Quart. Journ. Geol. Soc.*, 1885, p. 311.

Carboniferous to *Recent*. Common in *Carboniferous*.

Cythere (fig. 124, *c*).—Shell thick, oval, or somewhat rectangular; often very highly ornamented with knots or spines. Right valve with a tooth at each end of the hinge-line, and a pit and horizontal groove between them; left valve with terminal pits, a ridge, and an anterior tooth.

Gotlandian to *Recent*.

Primitia.—Shell small, thick, elongated oval; but hinge-border straight. Not always equivalve. A furrow runs on the surface from the hinge-border vertically towards the ventral border, sometimes reaching as far as the centre of the valve.

Cambrian to *Carboniferous*. Especially *Ordovician* and *Gotlandian*.

Beyrichia (fig. 125).—Shell thick, surface distinctly convex; straight hinge. Somewhat truncated anterior and posterior borders, and convex ventral border. Surface divided by strong fairly vertical furrows into markedly convex lobes, which commonly unite below; the marginal area is smoother.

Cambrian to *Carboniferous*. Especially *Ordovician* and *Gotlandian*.

Leperditia (fig. 126).—Shell large (attaining 2 cm. in length), thick, rather bean-shaped; straight hinge-border, and convex ventral border. Anterior border shorter than posterior. Right valve larger than, and lapping somewhat over, the left. A small eye-spot occurs near the hinge-border.

Cambrian to *Carboniferous*. Especially *Ordovician* and *Gotlandian*.

B. Phyllopoda.

The animal is more distinctly segmented than in the Ostracoda, and the thoracic limbs, often numerous, are flattened and leaf-like, each dividing into two flaps at the end. Many genera have a covering that recalls the ostracod shell. Compare also the Phyllocarida.

Estheria.—Shell bivalve, thin, sometimes partly calcified, but commonly horny, with a polished appearance. A small rounded umbo occurs near the anterior margin; hinge-line toothless and straight. Ventral border convex. Surface in most species concentrically ribbed; sometimes smooth.

Prof. T. Rupert Jones* remarks that, while Estheriæ have

* *Fossil Estheriæ*. Palæont. Society, 1862, pp. 12 and 13.

often been mistaken for small forms of Avicula and Posidonomya, their horny appearance will distinguish them from the former, while there is also an absence of any bending out of the concentric markings towards an ear, such as Avicula possesses. The valves, moreover, are rarely so quadrate in form as those of Posidonomya.

Fresh and Brackish water; but early forms are found associated with Marine fossils, perhaps owing to floods, perhaps through difference of habit.

Devonian to *Recent.* Fairly common in the *Trias.*

C. Trilobita.

Owing to the absolute extinction of the whole order, the relations of the Trilobites to the well-defined Crustacea and to the Arachnida have remained somewhat obscure. Thanks to the work of Messrs. E. Billings,* C. D. Walcott,† and J. Mickleborough,‡ the appendages of the genera Asaphus, Calymene, Cheirurus, and Acidaspis, are now fairly known; while Mr. Beecher has examined them in Trinucleus and, with signal success, in Triarthrus.§ Dr. Oehlert has recently summarised the results of these researches (*Bull. Soc. géol. de France*, 3me sér., t. xxiv., p. 97); and it has been pointed out that Linnæus observed antennæ in a specimen of Parabolina as far back as 1759 (see *Geol. Mag.*, 1896, p. 142). The verification of these in Triarthrus has led to the retention of the trilobites among the Crustacea; and Mr. H. M. Bernard sees in Apus their nearest living representative. Some valuable considerations on the segmentation and limbs of trilobites are given by O. Jaekel (*Zeitschr. deutsch. geol. Gesell*, Bd. liii., 1901, p. 133).

The hard covering of the trilobites, which is all that ordinarily remains to us can be clearly divided into three parts, the nomenclature of which has depended upon the classificatory position taken up by successive palæontologists. The supporters of the arachnid view employ "cephalo-thorax," "abdomen," and "post-abdomen" or "pygidium"; the rival school uses "head," "thorax," and "pygidium." To avoid confusion, and to carry forward the same nomenclature when writing of the Merostomata, we propose to speak of the "head-shield," "body," and "pygidium." This is practically the plan adopted by Mr. H. M. Bernard.

Head-shield (fig. 127).—This portion is approximately semicircular, and is not broken up in the adult into transverse

* *Quart. Journ. Geol. Soc.*, vol. xxvi. (1870), p. 479.
† *Bulletin Museum Comp. Zoology, Cambridge, U.S.A.*, 1881.
‡ Reprinted in *Geological Magazine*, 1884, pp. 80 and 162.
§ *Am. Journ. Sci.*, 1895 and 1896, and 4th ser., vol. xiii. (1902).

segments. It has curved *anterior* (or *frontal*) and *lateral borders*, forming an outwardly convex margin; while it has an almost straight posterior or *occipital border*, where it joins the first body-segment. An *occipital furrow* often occurs in the head-shield parallel to and near this border. The shield is folded over below its front margin, so as to extend a little way back towards the mouth.

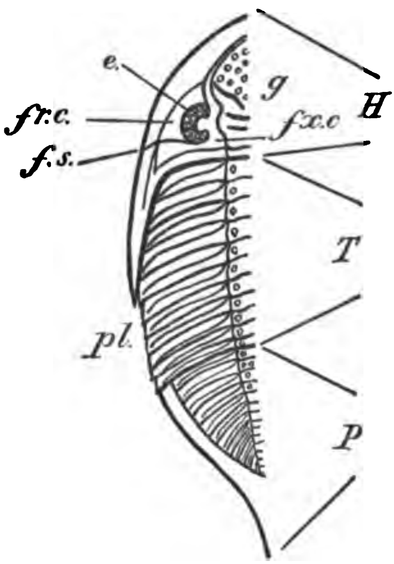

Fig. 127.—Trilobite (*Dalmania caudata*; Wenlock Beds). *H*, Head-shield; *T*, Body-segments; *P*, Pygidium. *e*, Eye. *fx.c*, Fixed cheek. *fr.c*, Free cheek. *fs*, Facial suture (starting in this example from the lateral margin and finally passing round in front of the glabella). *g*, Glabella (bearing lateral furrows). *pl*, Pleura.

In young forms, the original segments composing the head-shield have been traced. O. Jaekel regards these as always eight, including the hypostome as the first.

Glabella.—The convex elevated portion of the head-shield reaching from the centre of the occipital border nearly to the anteriorborder. Theglabella varies in form, and sometimes bears lateral furrows, which run approximately at right angles to its sides; they thus divide its edges into *lobes*, and probably represent traces of original segmentation.

Facial Sutures.—Fine lines of junction between the two parts into which the area on either side of the glabella can be divided. Each of the two facial sutures arises at some posterior point of the border of the head-shield, runs forward between the glabella and the eye, and either terminates by cutting across the anterior border (fig. 128), or by meeting its fellow-suture in front of the glabella (fig. 132). Occasionally in the former case an additional suture, the *marginal suture*, runs from one facial suture to the other along the anterior part of the head-shield, as in Calymene, Paradoxides, and Illænus.

Fixed Cheeks.—The areas on each side of the glabella between it and the facial suture.

Free Cheeks.—The portions of the head-shield between the facial sutures and the outer margin. These two parts may become detached after the death of the animal, and are often seen to have shifted away slightly from the fixed cheeks.

Eyes.—These are sometimes absent (fig. 130), sometimes represented only by papillæ; but they are commonly present as two somewhat crescentic elevations, occasionally supported on a stalk, and are covered with numerous facets, each of which was a lens (figs. 127 and 135). As above hinted, they occur on the free cheeks, close against the facial suture, where it approaches the side of the glabella.

Hypostome.—The anterior portion of the head-shield is bent over, and may form a broad crescentic plate-like surface on the under side, between the anterior end of the animal and the position occupied by its mouth. A small plate, of various form, often occurs before the mouth, with its anterior border in contact with the edge of the folded-over head-shield, and its other borders free. This is the Hypostome (fig. 133), representing the labrum that overlaps the front of the mouth in higher crustacea. Two sense-organs (? eyes) occur on it in some genera.

Body.—The portion between the head-shield and the pygidium. It consists of a very variable number of segments, which were movable on one another, so that in some genera the animal could coil itself up after the manner of a wood-louse. Two longitudinal furrows or depressions run down the body, one starting on each side of the glabella, and corresponding, in fact, to the depressions which divide the glabella from the cheeks. Each body-segment is thus marked out into a central convex part, the *annulus*, and a flatter and commonly broader portion on each side. The latter areas form the *pleura*;* they are generally marked with a groove, or a ridge, from the annulus outwards, and often terminate in spines (fig. 128). The convex ridge formed by the series of annuli, running from the glabella over the body, and commonly on to the pygidium itself, is termed the *rachis*.

Pygidium.—The shield covering the posterior part of the trilobite. Its outline often repeats that of the head-shield (figs. 129 and 133), and it consists of permanently united segments. Sometimes the traces of the original segmentation are perfectly clear (fig. 134), and the rachis generally persists on it for some distance.

* *Pleura* and *pleuræ* have alike been used; their respective singulars are *pleuron* and *pleura*, both of which are good Greek forms.

Appendages.—Of the five pairs of head-appendages known, the first is a pair of *antennæ*, their bases inserted on the edge of the hypostome. These are long in Triarthrus, and consist of one ray. The bases of the remaining four pairs were probably used in mastication. Each body-segment bore a pair of appendages, and the pygidium had also a number of pairs corresponding to its original segmentation. All these limbs were fixed to the inside edges of the rachis. They were simple biramous types; and the pygidial pairs, and possibly those on the body, served for respiration as well as for swimming. There is a gradual change in type, from the anterior body-appendages, which resemble those on the head-shield, to the posterior ones, which resemble those on the pygidium.

Lastly, we should note that the more resisting character of the head-shield and the pygidium often allows of their being found isolated in rocks, when the body-segments have become parted asunder and lost. It has been suggested that the "trilobite," as found, may often be a mere "skin" cast off by the animal during life.

The Trilobites were all Marine.

Paradoxides.—Form elongated; sometimes large (70 cm. or so in length), tapering fairly uniformly from the front to the pygidium. Head-shield semicircular, with a long curving spine running backwards from each of its posterior angles. Glabella rather flat, rounded and broad in front, narrowing posteriorly, with lateral furrows. Facial sutures running from posterior to anterior border, without bending in any great degree towards the glabella. A marginal suture is present. Body with numerous (16 to 20) segments, and with well-marked trilobed character. Pleura furrowed and prolonged as spines. Pygidium very small, the rachis being continued on to it for a short distance; a long spine often runs out posteriorly on each side.

Exclusively *Cambrian*. Typically *Middle Cambrian*.

Olenellus.—Resembles Paradoxides, with narrower glabella; facial sutures obscure or absent. Third body-segment often larger than the others. Pygidium at times styliform. 13 to 26 body-segments.

*Lower Cambrian.**

* See "The Story of Olenellus," *Natural Science*, vol. i., p. 340. *Holmia* and *Mesonacis* are subgenera.

Olenus (fig. 128).—Form broader and more oval than in Paradoxides. Head-shield broad and semicircular, with a spine running back from each posterior angle. Glabella rather conical, narrowing anteriorly, and with lateral furrows. A little ridge runs out from it to each eye, at right angles to the axis. Facial suture running from posterior to anterior border, sometimes closely approaching glabella. Body with 12 to 15 segments, which have short sharp backward terminations. Pleura broad. Pygidium small, broad, with rachis well marked on it for some distance.

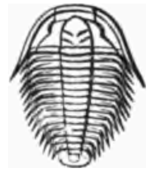

Fig. 128.—*Olenus micrurus* (Lingula Flags).

Exclusively *Cambrian*. Typically *Upper Cambrian*.

Conocoryphe (Conocephalus).—Form much like Olenus. Head-shield semicircular, without posterior spines. Glabella conical, furrowed; somewhat truncated at its narrower (anterior) end, and divided by deep depressions from the cheeks. Eyes rather near the anterior end of the glabella, and facial sutures running from the posterior margin, near the angles of the shield, inwards almost to the glabella, and then out, widely diverging, across the anterior border. Body with fourteen or fifteen segments; rachis well marked; pleura furrowed, and rounded at the ends. Pygidium small, with distinct rachis, and with traces of segmentation.

L. Cambrian to *Ordovician*.

Angelina.—Proportions much as in Olenus, and head-shield with posterior spines. Glabella narrowed anteriorly, but smooth and rounded. Body with fourteen or fifteen segments; pleura furrowed.

Cambrian.

Agnostus (fig. 129).—Form small, elliptical, the head-shield

Fig. 129.—*Agnostus* (Cambrian).

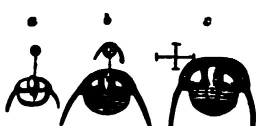

Fig. 130.—*Trinucleus concentricus* (Bala Beds). In various stages of growth.

Fig. 131.—*Harpes Flanagani* (Bala Beds).

and pygidium being almost similar; both are rounded at the outer end, with convex or straightish sides. Glabella distinct.

No eyes or facial sutures. Body with only two segments. Pygidium with fairly marked rachis, which terminates broadly; a little process often runs out posteriorly from each lateral border of the pygidium; but it is otherwise difficult to distinguish detached pygidia from head-shields.

Cambrian.

Trinucleus (fig. 130).—Head-shield large and predominant, projecting laterally beyond the body; semicircular in front, and often with long spines from the posterior angles. Glabella and cheeks smooth, and forming three strongly convex elevations, which leave a broad flat semicircular border beyond them. This border is pierced with minute holes. No eyes or facial sutures. Body with six segments; rachis rather narrow and distinct, continued on to the small pygidium; pleura furrowed. The body and pygidium are together smaller in area than the head-shield.

Ordovician.

Harpes (fig. 131).—This remarkable form bears some resemblance to Trinucleus, having a similar broad perforated border to the head-shield, prolonged backwards in this case almost as far as the pygidium. Eyes present, but no (or very indistinct) facial structures. A little ridge sometimes runs from the glabella to each eye, as in Olenus. Numerous body segments (about twenty-five). Pygidium very small. The flat border of the head-shield is sometimes found detached and isolated.

Ordovician to *Devonian.*

Calymene.—Form oval, rather broad. Often ornamented with little tubercles. Head-shield broad, rounded anteriorly; posterior angles generally without spines. Glabella convex, with three strong pairs of furrows, the most posterior pair in some species bifurcating at the end. Facial sutures running from the posterior angles obliquely inwards to the eyes, and then across the anterior border, where they are connected by a marginal suture. Body with thirteen segments; rachis well marked. Pygidium rounded and scarcely distinct from the body, the rachis reaching to the end, and traces of segments being clearly marked.

This genus is one of those most frequently found in a rolled up condition, as in the specimens from the Wenlock Beds at Dudley. The hindmost of the pairs of limbs on the head-shield is larger and broader than the others, suggesting its differentiation into a special pair of paddles.

Ordovician and *Gotlandian.*

Homalonotus (fig. 132).—Form fairly long; sometimes ornamented with spines. Head-shield rather broad, either rounded or pointed anteriorly; no posterior spines. Glabella commonly only feebly marked off from the cheeks, and unfurrowed. Facial sutures much as in Calymene, but commonly meeting without intersecting the anterior border. Body with thirteen segments; rachis not sharply marked off. Pygidium with rachis and traces of segments; pointed posteriorly, sometimes ending in a short spine.

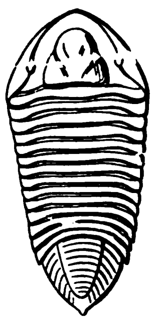

Fig. 132.—*Homalonotus* (Gotlandian). Showing facial suture continuous in front of the glabella.

Fig. 133.—*Asaphus Powisii* (Ordovician). With hypostome.

Ordovician to *Devonian*.

Ogygia.—Form often large, roundly oval, and rather flat. Head-shield semicircular, sometimes with posterior spines. Glabella rather straight at sides, widening in front, with four pairs of furrows. Hypostome not notched on its posterior border. Facial sutures running from the posterior border, near the angles, obliquely to the large crescentic eyes; thence they sometimes cross the anterior border, but generally unite in front of the glabella. Body with 8 segments; rachis well marked; pleura broad, furrowed, not spinose at the ends. Pygidium about the same size as the head-shield, and nearly semicircular, slightly

elongated; its rachis is distinct, with numerous segmental markings on it and on the lateral areas.

Ordovician.

Asaphus (fig. 133).—A close ally of Ogygia, and often large. Like Ogygia, but rather more convex; 8 body-segments. The traces of segmentation on the pygidium are confined to its rachis or altogether absent. The head-shield may be sharply pointed in front, or semicircular; glabella commonly not furrowed. Hypostome with a deep notch on posterior border. The glabella on the head-shield and the rachis on the pygidium may appear merely as broadly convex folds.

Ordovician.

Illænus.—Ally of Asaphus, but commonly more strongly convex, and more broadly elliptical in outline. Glabella only feebly indicated, externally without furrows. Facial sutures connected by a marginal suture; 8 to 10 body-segments (typically the latter); pleura smooth. Pygidium with slight trace, if any, of rachis, and with no external signs of segmentation.

Ordovician and *Gotlandian.*

Phacops (fig. 134).—Form elongated, oval, or elliptical. Head-shield almost semicircular, without posterior spines. Glabella

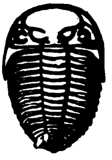

Fig. 134. — *Phacops* (*Chasmops*) *conophthalmus* (Bala Beds). In the sub-genus Chasmops the anterior lobes of the glabella are exceptionally expanded.

Fig. 135. — *Bronteus flabellifer* (Devonian).

much widened anteriorly, distinct; only feebly furrowed, except in the posterior part. Facial sutures arising on the lateral margins, almost opposite the eyes, and uniting in front of the glabella. Body with 11 segments. Pygidium semicircular, with marked rachis and signs of segmentation. See Dalmania.

Gotlandian to *Devonian.*

Dalmania (fig. 127).—Like Phacops, of which it is often regarded as a mere sub-genus; but the glabella is distinctly furrowed, and not so markedly widened anteriorly. Long posterior spines to the head-shield; the pygidium also commonly terminates in a spine.

Ordovician and *Gotlandian*.

Bronteus (fig. 135).—Form broadly oval. Head-shield semicircular; free cheeks often detached; glabella much widened anteriorly, and sometimes furrowed. Ten body-segments; pleura with longitudinal ridges. Pygidium large, rounded posteriorly, with very short rachis, from which somewhat broad furrows radiate to the margin.

Ordovician to *Devonian*.

The last family, the Proetidæ, contains the latest surviving trilobites.

Proetus.—Form small; oval or elliptical. Head-shield semicircular, with a distinct thickened marginal rim; posterior spines sometimes occur. Glabella convex, somewhat narrowed in front; unfurrowed. Facial sutures running rather straightly from the posterior to the anterior border. Eight to ten body-segments; rachis distinct, pleura furrowed. Pygidium with a semicircular border like that of the head-shield, the whole form being thus simple and elliptical.

Ordovician to *Carboniferous*. Typically *Lower Palæozoic*.

Phillipsia.—Close ally of Proetus; but the glabella bears three pairs of furrows, and is bounded by nearly parallel sides. Nine body-segments. The smooth elliptical outline of Proetus is maintained in Phillipsia.

Gotlandian to *Permian*; typically *Carboniferous*.

Griffithides.—Like Phillipsia, of which it may be regarded as a mere sub-genus; but glabella distinctly widened in front, with one pair of furrows only, these being posterior.

Carboniferous.

D. Merostomata.

This group of arthropods, represented at present by the King-Crab (Limulus), attains importance on account of the great size of many of its forms. Aglaspis of the American Cambrian is regarded as an early limuloid, and Neolimulus and Hemiaspis

are allies from the British Gotlandian. The Eurypterida range from the Cambrian to the Carboniferous.

Here, again, the nomenclature of the parts of the animals depends upon the classification adopted. The arachnid view gives us "cephalo-thorax," "abdomen," and "post-abdomen"; the crustacean view, "head-shield," "thorax," and "abdomen." We propose to adopt "head-shield," "body," and "posterior region," in order to avoid debatable ground, and to compare the Merostomata fairly with the Trilobites.

(i) Xiphosura.

Belinurus is an early ally of Limulus, with hemispherical head-shield, 5 unfused body-segments, and 3 fused posterior segments, this region terminating in a long spine. Having a glabella, rachis, and furrowed pleura, it has a decidedly trilobitic character.

Fig. 136.
Prestwichia rotundata (Carboniferous).

Devonian (*U. Old Red Sandstone*) and *Coal-Measures.*

Prestwichia (fig. 136) is like Belinurus, but its body-segments are fused, as well as those of the posterior region.

U. Devonian to *Permian.*

Prolimulus, resembling a larval Limulus, occurs in the *Permian* of Bohemia.

Limulus itself, with its fused body-segments, and no other representative of the posterior region than a spine, occurs as early as the *Trias.* The larva of Limulus, with its separate head-shield, marked with a glabella, and its segmented body, presents a striking resemblance to Prestwichia, and is to the geologist one of the most interesting of living creatures.

(ii) Eurypterida.

The Eurypterida include animals some four or even six feet long, the appendages attached to the head-shield being highly developed and of very various form. The body has six unfused segments, with branchiæ, which are connected with plate-like appendages, occurring on their under sides; there are seven posterior segments, also movable, the last consisting of a *telson*, as in the familiar Crayfish. The whole surface preserves only traces of a trilobed character, and is more or less folded over in the body and posterior regions. The whole form is long,

but somewhat pear-shaped. For a general review, see Laurie, *Trans. R. Soc. Edinburgh*, vol. xxxvii. (1893), p. 509.

Eurypterus has a somewhat semicircular head, rather straight at the sides, with a large pair of eyes set well within the margin; "ocelli" or eye-spots occur in addition in the centre of the shield. The work of Dr. Fr. Schmidt* has revealed an additional small pair of appendages, not reaching to the margin of the head-shield, and in advance of those previously known. This first pair is now known to be provided with prehensile claws (chelæ), and behind it come four larger pairs of simple limbs. The sixth and last pair consists of large flattened swimming-paddles.

Schmidt brings forward evidence to show that the body-segments bend over comparatively slightly at the sides, as in ordinary trilobites, and that the plates which seem to continue them on the under-side, thus covering the branchiæ, belong in reality to the branchial (phyllopodous) appendages themselves.

The telson, in opposition to that of Pterygotus, is a long spine.

Uppermost *Gotlandian* to *Carboniferous*.

Pterygotus is generally similar in form to Eurypterus, but its two large eyes lie on the anterior margin of the head-shield. The first appendage on each side is long, and terminates in a claw like that of the lobster. Schmidt † finds four smaller simple pairs of appendages behind this one—not three as usually figured; the sixth, as in Eurypterus, is a pair of broad swimming-paddles. The telson is also broad and paddle-shaped.

Ordovician (Bohemia) to *Devonian* (*Old Red Sandstone*).

Stylonurus resembles Eurypterus, and has similarly a spine for the telson; but its two posterior pairs of limbs are very long, resembling jointed rods.

Uppermost *Gotlandian* to *Devonian*.

E. Leptostraca (Phyllocarida).

This division of the Crustacea has been formed to include the small living genus Nebalia, which has characters intermediate between some Entomostraca and the Malacostraca. As in the latter division, the head and thorax together include thirteen

* "Die Crustaceenfauna der Eurypterenschichten von Rootziküll auf Oesel." *Mém. Acad. imp. des Sciences de St. Petersbourg*, sér. 7, tome xxxi. (1883), p. 51, &c.

† *Ibid.*, p. 64.

segments; but Nebalia is peculiar in having eight abdominal segments. The thoracic limbs ally Nebalia to the Phyllopods; and it has, like Apus in that group, a thin dorsal shield, folded over laterally, and covering the cephalic and thoracic segments. On the other hand, it has a characteristic appendage, the *rostrum*, in front of the shield. Nebalia is Marine.

Several well-known Palæozoic genera have been transferred here from the Phyllopoda, on account of the fairly constant number of their segments, the presence of a rostrum, &c. But much caution must necessarily be exercised in dealing with their thin and fragmentary remains.

Ceratiocaris.—Dorsal shield bivalve, somewhat rectangular when viewed from the side. Fourteen or more segments, of which sometimes as many as seven are free, and project beyond the dorsal shield. Surface of shield finely striated parallel to its length. Rostrum known. Abdomen terminating in a telson, which is formed of a large and two shorter spines.

Ordovician to *Carboniferous*.

Hymenocaris.—Dorsal shield composed of one piece folded over, distinctly convex at the ventral border. Telson with several spines.

Cambrian (*Lingula Flags*).

F. Malacostraca.

In this division, including the modern types of highly-organised Crustacea, the animal has typically six head-segments (some authors, reckoning in the eye, have counted seven), seven thoracic segments, and seven abdominal segments, including the telson.

While fossil remains of Malacostraca occur scattered fairly freely through Mesozoic and Cainozoic rocks, they are scarcely to be regarded as of importance in characterising special horizons.

Archæoniscus may be mentioned as an early representative of the Isopoda, the order that includes the Woodlouse (Oniscus). The isopods have the head distinct from the thoracic segments; the form is broadly oval, and the branchiæ are borne by the fused abdominal segments. In Archæoniscus there are thirteen thoracico-abdominal segments, including a rounded telson. Milne-Edwards assigns seven of these to the thorax.

Purbeck.

As an example of the Macrurous Decapoda, which include the Lobster, we may mention **Hoploparia**, in which there is the

characteristic fusion of the anterior segments into a cephalothoracic shield. One of the two great anterior clawed limbs is more slender than the other.

Lower Cretaceous to *Eocene* (*London Clay*).

Lastly, **Palæocorystes** (*Gault* to *Eocene*), and **Xanthopsis** of the *Cretaceous* and *Eocene*, are familiar Brachyurous Decapods; they are crab-like, therefore, in form, with the abdomen, unlike that of the Macrura, folded under the broad cephalothoracic shield.

CHAPTER XXVIII.

SUGGESTED LIST OF CHARACTERISTIC INVERTEBRATE FOSSILS.

As already mentioned (p. 292), this list consists in great part of forms familiar in the British Isles, and must be modified to suit the needs of observers in any special area. Some rare forms are included, where they mark important zones, or where they are a distinct addition to the fauna as displayed by other genera. Attention is particularly directed to the generic names, since these give an idea of the faunæ of successive periods, in whatever country the student may be placed. On going over the list in front of the specimens in a public collection, notes may conveniently be added as to specific characters. A few such notes are given here; but to ascertain the real points of difference between one species and another of the same genus, reference must be made to the original descriptions, or to publications such as those of the Palæontographical Society. Dr. E. Koken, in his *Leitfossilien* (C. H. Tauchnitz, Leipzig, 1896), enters usefully into the specific details of a large number of characteristic fossils. Where synonyms exist, the more familiar names of genera have been adopted; and where a new genus has been established out of a subdivision of an old one, the older name is often also given.

Abbreviations used :— Hydro. = Hydrozoa. Actin. = Actinozoa. Brach. = Brachiopoda. Lam. = Lamellibranchiata. Gast. = Gastropoda. Ceph. = Cephalopoda. *Am.* = *Ammonites.*

I. CAMBRIAN.

Lower Series (Olenellus Series; Taconian, Lapworth, 1891).

Spongiæ. *Protospongia.*
Brach. *Lingulella primæva.*
Pteropoda? *Hyolithes antiquus.*
Trilobita. *Olenellus.*

Middle Series (Menevian; Paradoxides Series).

Spongiæ. *Protospongia fenestrata.*
Brach. *Discina pileolus. Obolella sagittalis.*
Pteropoda? *Hyolithes corrugatus.*
Trilobita. *Paradoxides Davidis. Conocoryphe coronata. Agnostus scutalis.*

Upper Series (Olenus Series).

Lingula Flags Stage.

Brach. *Lingulella Davisii. Orthis lenticularis.*
Trilobita. *Agnostus pisiformis.*
Phyllocarida. *Hymenocaris vermicauda.*

Tremadoc Stage.

Hydro. *Dictyonema sociale.*
Brach. *Orthis Carausii. Lingulella lepis.*
Lam. *Cyrtodonta* and *Glyptarca,* an early ally of Arca (rare).
Pteropoda. *Hyolithes. Conularia.*
Trilobita. *Olenus. Conocoryphe depressa. Angelina Sedgwicki.*

II. ORDOVICIAN (LOWER SILURIAN).

Arenig Series.

Hydro. *Didymograptus. Diplograptus.*

Llandeilo Series.

Hydro. *Didymograptus Murchisoni.*
Brach. *Orthis striatula.*
Gast. *Bellerophon perturbatus.*
Trilobita. *Ogygia Buchii. Asaphus tyrannus. Trinucleus. Calymene.*

Bala Series.

Hydro. *Diplograptus. Climacograptus.*
Brach. *Orthis calligramma. Orthis flabellulum.*
Ceph. *Orthoceras vagans.*
Cystidea. *Echinosphærites.*
Trilobita. *Trinucleus concentricus. Illænus. Phacops Brongniarti.*

III. GOTLANDIAN (UPPER SILURIAN).

Llandovery Series.

Hydro. *Diplograptus vesiculosus. Monograptus Sedgwicki. Rastrites peregrinus.*
Brach. *Pentamerus oblongus* (common as casts in England).
Trilobita. *Proetus Stokesii.*

Wenlock Series.

Hydro. *Monograptus priodon. Stromatopora.*
Actin. *Heliolites interstinctus. Halysites catenularia* (also in Bala Series). *Omphyma turbinatum. Cyathophyllum angustum. Favosites gothlandica. Alveolites. Cœnites.*
Polyzoa. *Fenestella.*
Brach. *Rhynchonella borealis. Orthis elegantula. Leptæna rhomboidalis. Atrypa reticularis. Meristella tumida.*
Lam. *Orthonota amygdalina.*
Gast. *Euomphalus rugosus. Pleurotomaria. Murchisonia.*
Pteropoda? *Tentaculites.*
Ceph. *Orthoceras annulatum. Phragmoceras. Gomphoceras.*
Crinoidea. *Actinocrinus. Cyathocrinus.*
Trilobita. *Calymene Blumenbachii. Homalonotus delphinocephalus. Dalmania caudata* (*Phacops caudatus*).

Ludlow Series.

Brach. *Pentamerus Knightii* (Aymestry Limestone).
Lam. *Cardiola interrupta. Orthonota. Grammysia.*
Ceph. *Orthoceras ludense. Lituites.*
Eurypterida. *Eurypterus. Pterygotus. Stylonurus.*

IV. DEVONIAN.

Lower Series.

Brach. *Spirifer speciosus.*
Lam. *Grammysia marginata.*

Ceph. *Orthoceras.*
Trilobita. *Bronteus.* *Homalonotus.*

Middle Series.

Actin. *Cyathophyllum helianthoides.* *Favosites cornigera.* *Calceola sandalina.*
Brach. *Stringocephalus Burtini.* *Spirifer elegans.* *Pentamerus galeatus.*
Gast. *Bellerophon striatus.* *Pleurotomaria.* *Murchisonia.*
Crinoidea. *Actinocrinus.*
Trilobita. *Phacops latifrons.* *Bronteus flabellifer.*

Upper Series.

Hydro. *Stromatopora.*
Brach. *Atrypa reticularis* (passes up from Silurian). *Rhynchonella cuboides.* *Spirifer Verneuili.*
Lam. *Cucullæa unilateralis* (*Hardingii*). *Cardiola.*
Ceph. *Clymenia.* *Prolecanites* (*Goniatites*).

Old Red Sandstone (Fresh-water Devonian).

Lam. *Archanodon Jukesii* (passage-beds to L. Carboniferous).
Phyllopoda. *Estheria.*
Eurypterida. *Eurypterus.* *Pterygotus.* *Stylonurus.*

V. CARBONIFEROUS.

Foraminifera. *Endothyra.* *Fusulina.* *Saccammina fusuliniformis.*
Actin. *Cyathophyllum regium.* *Zaphrentis* (*Caninia*) *cylindrica.* *Lithostrotion basaltiforme.* *Lonsdaleia floriformis.* *Michelinia favosa.* *Syringopora ramulosa.*
Polyzoa. *Fenestella.* *Entalophora.*
Brach. *Spirifer striatus.* *Productus semireticulatus.* *Productus giganteus.* *Orthis resupinata.* *Rhynchonella pugnus.* *Terebratula hastata.*
Lam. *Posidonomya Becheri.* *Aviculopecten* (*Pterineopecten*) *papyraceus.* *Conocardium aliforme.* *Carbonicola aquilina* and other species (freshwater beds).
Gast. *Euomphalus pentangulatus.* *Bellerophon.* *Naticopsis.* *Pleurotomaria.*
Pteropoda. *Conularia.*

Ceph. *Orthoceras*. *Discites*. Goniatites : — *Glyphioceras crenistria* ; *Gastrioceras Listeri* ; *Pronorites cyclolobus*.

Crinoidea. *Actinocrinus*. *Platycrinus*. *Cyathocrinus*.

Blastoidea. *Granatocrinus ellipticus*. *Pentremites*.

Trilobita. *Griffithides seminiferus* (*Phillipsia seminifera*). *Phillipsia gemmulifera*.

VI. PERMIAN.

Polyzoa. *Fenestella retiformis*.

Brach. *Productus horridus*. *Camarophoria multiplicata*.

Lam. *Schizodus truncatus*.

Gast. *Bellerophon*.

VII. TRIAS.

Lower Series (Bunter and Werfen Series).

Lam. *Myophoria costata* (Bunter). *Modiola hirundiformis* (Bunter). *Monotis Clarai* (Werfen). *Trigonia costata* (Bunter and Werfen ; also M. Jurassic).

Ceph. *Trachyceras*, and other allies of *Ceratites* (Werfen ; *Beneckeïa*, among these, occurs also in Bunter).

Phyllopoda. *Estheria Albertii* (Bunter).

Middle Series (Muschelkalk Series).

Brach. *Spiriferina Mentzeli*. *Terebratula vulgaris*. *Retzia* (*Tetractinella*) *trigonella*.

Lam. *Daonella Sturi* (Alps). *Lima* (sub-gen. *Radula*) *striata*. *Gervillia* (*Hœrnesia*) *socialis*. *Myophoria vulgaris*.

Ceph. *Orthoceras campanile* (Alps). Ammonites :—*Trachyceras*. *Ceratites nodosus*.

Crinoidea.—*Encrinus liliiformis* (*E. fossilis*).

Upper Series (Keuper and Upper Alpine Series).

Brach. *Koninckina Leonardi* (Alps).

Lam. *Daonella* (*Halobia*) *Lommeli* (Alps). *Cardita crenata* (Alps). *Gervillia subcostata*. *Myophoria Goldfussi*. *Myophoria raibliana* (Keuper and Alps).

Gast. *Turbo solitarius* (Alps).

Ceph. *Orthoceras elegans* (Alps). Ammonites:—*Arcestes subumbilicatus* ; *Arcestes Gaytani* ; *Trachyceras Aon* (Alps).

Echinoidea. *Cidaris* (Alps).
Phyllopoda. *Estheria minuta* (Keuper).

Rhætic.

Lam. *Monotis decussata*. *Avicula contorta*. *Pecten valoniensis*. *Protocardia rhætica*.

VIII. JURASSIC.

Lower Jurassic.

Lower Lias.

Brach. *Spiriferina Walcottii*.
Lam. *Avicula cygnipes* (also Middle Lias). *Cardinia Listeri*. *Cardinia ovalis*. *Hippopodium ponderosum*. *Gryphæa incurva*. *Lima* (sub-gen. *Plagiostoma*) *gigantea*.
Gast. *Pleurotomaria anglica*.
Ceph. Ammonites :—*Psiloceras planorbis; Schlotheimia angulata* (*Ægoceras angulatum*)*; Arietites Conybeari; Arietites Bucklandi; Arietites obtusus; Oxynoticeras* (*Amaltheus*) *oxynotus; Arietites raricostatus; Ægoceras planicosta*.
Crinoidea. *Pentacrinus*.

Middle Lias.

Brach. *Terebratula punctata*. *Rhynchonella tetrahedra*.
Lam. *Pecten æquivalvis*.
Ceph. Ammonites :—*Amaltheus margaritatus; Amaltheus spinatus; Ægoceras capricornus; Ægoceras Henleyi; Ægoceras armatum*.

Upper Lias.

Lam. *Leda ovum*.
Ceph. Ammonites :—*Phylloceras heterophyllum; Cœloceras commune; Harpoceras* (*Hildoceras*) *bifrons; Harpoceras serpentinum*. *Belemnites* often abundant.

Middle Jurassic.

Midford Sands.

Brach. *Rhynchonella cynocephala* (ventral margin strikingly plicated).
Lam. *Pholadomya fidicula*.
Ceph. *Lytoceras jurense* (*Ammonites jurensis*). This species has several auxiliary lobes, contrary to the rule in Lytoceras.

Inferior Oolite.

Actin. *Montlivaltia.*

Brach. *Terebratula fimbria. Rhynchonella spinosa.*

Lam. *Lima* (sub-gen. *Ctenostreon*) *proboscidea. Trigonia,* numerous species; e.g., *Trigonia costata. Ceromya bajociana.*

Gast. *Pseudomelania* (*Chemnitzia*). *Nerinea.*

Ceph. Ammonites:—*Parkinsonia* (*Cosmoceras*) *Parkinsoni; Stephanoceras humphriesianum.*

Echinoidea. *Clypeus Plotii. Pygorhytis ringens* (Pygorhytis is one of the Collyritidæ).

Bathonian.

Brach. *Terebratula maxillata* (note the range of form in this species). *Waldheimia digona. Rhynchonella concinna.*

Lam. *Gresslya peregrina. Gervillia acuta. Homomya gibbosa.*

Crinoidea. *Apiocrinus Parkinsoni* (*A. elegans*).

Echinoidea. *Echinobrissus clunicularis.*

Upper Jurassic.

Oxford Clay.

Lam. *Alectryonia* (*Ostrea*) *Marshi. Gryphæa dilatata. Trigonia elongata* (also in Kimeridge Clay).

Ceph. Ammonites:—*Cosmoceras Jason; Cosmoceras calloviense* (Kellaways Rock). *Nautilus hexagonus. Belemnites Oweni* (= *puzosianus*).

Coralline Oolite.

Actin. *Thecosmilia annularis. Thamnastræa arachnoides.*

Lam. *Trigonia clavellata. Goniomya v-scripta.*

Gast. *Bourguetia* (*Phasianella*) *striata. Pseudomelania* (*Chemnitzia*) *heddingtonensis. Nerinea Goodhalli.*

Ceph. *Amaltheus* (*Cardioceras*) *vertebralis* (also in upper zone of Oxford Clay). *Belemnites abbreviatus.*

Echinoidea. *Cidaris florigemma.*

Kimeridge Clay.

Brach. *Rhynchonella inconstans.*

Lam. *Ostrea deltoidea. Exogyra virgula.*

Ceph. *Holcostephanus pallasianus.**

* See Miss Healey, *Quart. Journ. Geol. Soc.*, vol. lx. (1904), p. 60.

Portland Beds.

Actin. *Isastræa oblonga* (best known by its casts in flint, in which the white parts represent the infilling of the calyx, and the darker more transparent portions the replacement of the septa and wall. In this species there is no columella, and the septa are strongly marked with lateral granules).

Lam. *Trigonia gibbosa.*

Gast. *Cerithium portlandicum* (best known by its screw-like casts).

Purbeck Beds.

Lam. *Cyrena. Ostrea distorta.*

Gast. *Paludina. Limnæa.*

Crustacea. *Cypridea punctata. Cypridea granulosa. Cypris purbeckensis. Archæoniscus Brodiei.*

Tithonian Stage (Basin of the Rhone).

Brach. *Pygope* and allied varieties of Terebratula.

IX. CRETACEOUS.

Lower Cretaceous.

Neocomian of France and Switzerland (Lower Neocomian of many authors). Compare with Lower Speeton Beds in England.

Lam. *Exogyra (Ostrea) Couloni. Perna Mulleti* (see Atherfielg Clay). *Janira atava.*

Ceph. Ammonites :—*Hoplites neocomiensis; Holcostephanus (Olcostephanus) astierianus. Crioceras (Ancyloceras) Duvalii. Belemnites lateralis.*

Echinoidea. *Toxaster complanatus.* (Toxaster is a close ally of Micraster; the ambulacra are open below, and the pores are slit-like.)

Wealden (Fresh-Water Passage-Beds from Upper Jurassic).

Lam. *Cyrena media. Unio valdensis.*

Gast. *Paludina elongata. Melania strombiformis.*

Ostracoda. *Cypridea valdensis.*

*BARRÊMIAN** or *URGONIAN* (Atherfield Clay).

Actin. *Holocystis elegans.*

Lam. *Gervillia anceps. Perna Mulleti* (found also in the Upper Speeton Beds). *Panopœa plicata.*

APTIAN (Hythe Beds and most of Folkestone Beds).

Spongiæ. Numerous spicules in the cherts.

Brach. *Terebratula sella* (also in the Atherfield Clay and Speeton Beds).

Lam. *Exogyra sinuata* (often large). *Plicatula placunea.*

Ceph. *Hoplites* (*Am.*) *Deshayesii* (in this species the median furrow common in Hoplites is absent; characteristic also of the Upper Speeton Beds).

ALBIAN or *SELBORNIAN*† (Gault, with uppermost part of Folkestone Beds).

Brach. *Kingena lima. Terebratula biplicata.*

Lam. *Exogyra conica. Inoceramus concentricus. Inoceramus* (sub-gen. *Actinoceramus*) *sulcatus. Nucula pectinata. Janira quinquecostata. Pecten orbicularis* and *asper* (also in Cenomanian).

Scaphopoda. *Dentalium decussatum.*

Gast. *Alaria carinata* (often called *Aporrhais.* This species has a narrowed tongue-like, and not broad, expansion of the outer lip).

Ceph. Ammonites :—*Acanthoceras* (*Douvilléiceras*) *mamillatum* (near base); *Hoplites interruptus; Hoplites lautus; Hoplites splendens; Schlœnbachia inflata* (= *rostrata*). *Hamites. Ancyloceras. Belemnites minimus.*

Upper Cretaceous.

CENOMANIAN (Lower Chalk Stage).

Spongiæ. *Plocoscyphia mæandrina.*

Lam. *Alectryonia* (*Ostrea*) *frons. Pecten asper.*

* See De Lapparent, *Traité de Géologie*, 3me. éd. (1893), pp. 1098 and 1118. Barrémian, due to Coquand in 1862, is the preferable term.

† See Jukes-Browne and Hill, as to correlation of beds styled "Upper Greensand" in England, *Mem. Geol. Surv.*, "Cret. Rocks of Britain" (1900), pp. 14-31.

Ceph. Ammonites:—*Acanthoceras rothomagense; Schlænbachia varians. Scaphites æqualis. Turrilites costatus. Actinocamax plenus* (*Belemnitella plena;* at top of series).

Echinoidea. *Discoidea cylindrica. Holaster subglobosus.*

Turonian (Middle Chalk).

Brach. *Terebratulina gracilis.*

Lam. *Inoceramus labiatus.*

Echinoidea. *Holaster planus.*

Senonian (Upper Chalk).

Spongiæ. *Doryderma. Ventriculites. Cliona cretacea* (known as borings, or casts of borings).

Brach. *Terebratula carnea. Terebratulina striata. Rhynchonella plicatilis. Crania.*

Lam. *Pecten nitidus* (a small almost smooth form). *Spondylus spinosus. Inoceramus Cuvieri. Inoceramus Brongniarti. Hippurites. Ostrea vesicularis.*

Ceph. *Belemnitella mucronata* (in higher beds).

Echinoidea. *Cidaris sceptrifera. Cyphosoma Kœnigi. Galerites albogalerus* (*Echinoconus conicus*). *Micraster coranguinum. Ananchytes ovatus* (*Echinocorys vulgaris*).

Danian.

Lam. *Ostrea vesicularis. Hippurites.*

Ceph. *Baculites Faujasi.*

X. EOCENE.

Lower Series (London Series).

Lower London Tertiaries.

Lam. *Ostrea bellovacina. Pectunculus terebratularis. Cyrena cuneiformis. Cyprina Morrisii.*

Gast. *Cerithium funatum. Melania inquinata. Natica subdepressa.*

London Clay.

Lam. *Pectunculus brevirostris. Pholadomya margaritacea. Teredo* (common in fossil wood).

Gast. *Turritella imbricataria. Aporrhais Sowerbyi. Pleurotoma teretrium* (and several other species). *Galerus* (*Calyptræa*) *trochiformis. Cassidaria nodosa.*
Ceph. *Nautilus imperialis.*
Annelida. *Ditrupa plana.*
Crustacea. *Hoploparia Belli. Xanthopsis Leachi.*

Middle Series (Bracklesham Series).

Foraminifera. *Nummulites lævigatus. Nummulites variolarius.*
Actin. *Litharæa Websteri.*
Lam. *Venericardia* (*Cardita*) *planicosta. Tellina speciosa* (and several other species).
Gast. *Cerithium giganteum. Murex minax. Pleurotoma attenuata. Conus diadema* (and several other species).

Upper Series (Barton Series).

Lam. *Crassatella sulcata. Cardita sulcata. Chama squamosa.*
Gast. *Rostellaria* (sub-gen. *Hippochrenes*) *ampla. Fusus* (sub-gen. *Clavella*) *longævus. Voluta luctatrix. Voluta ambigua.*

XI. OLIGOCENE.

Lower Series (Fluvio-marine Series of Isle of Wight).

Lam. *Cytherea incrassata* (the typical fossil of the marine bands). *Cyrena obovata. Cyrena semistriata. Ostrea vectensis. Corbula pisum.*
Gast. *Melania muricata. Melania costata. Melania turritissima. Melanopsis carinata. Cerithium mutabile. Cerithium plicatum. Cerithium elegans. Rissoa Chasteli. Neritina concava. Potamides concavus. Limnæa caudata. Limnæa longiscata. Planorbis euomphalus. Planorbis discus. Paludina lenta. Bulimus ellipticus. Helix globosa.*
Ostracoda. *Cypris.*

Upper Series (Aquitanian of Paris Basin and North Germany).

Gast. *Limnæa cornea. Potamides Lamarcki. Planorbis cornu. Helix Defrancei* (and several other species).

XII. MIOCENE.

Burdigalian * (Faluns of Bordeaux).

Gast. *Melania aquitanica*. *Hydrobia acuta* (in Mayence Basin).

Helvetian (Faluns of Touraine and Anjou in great part; Swiss Marine Mollasse).

Lam. *Ostrea crassissima*. *Lima squamosa*. *Arca turonica*.
Gast. *Trochus incrassatus*.
Echinoidea. *Scutella*.

Tortonian (of N. Italy, &c.).

Gast. *Pleurotoma* (numerous species). *Conus antiquus*. *Voluta varispina*. *Helix turonensis* (in Touraine).

XIII. PLIOCENE.

Pannonian (Sarmatian and Pontian of De Lapparent's Miocene System).

Lam. *Panopæa Menardi* (lowest beds). *Venus multilamella*. *Congeria* (several species).

Placentian (Coralline Crag).

Polyzoa. *Fascicularia aurantium*. *Eschara monilifera*. *Cellepora edax*.
Brach. *Terebratula grandis* (an unusually large species; found also in the Lenham Beds). *Lingula Dumortieri*.
Lam. *Pectunculus glycimeris* (also found in the Lenham Beds). *Astarte Omalei*. *Cardita senilis*. *Cyprina islandica* (also in higher Pliocene).
Gast. *Turritella incrassata*. *Voluta Lamberti*. *Cassidaria bicatenata*. *Ficula* (*Pyrula*) *reticulata*.
Echinoidea. *Echinus Woodwardii*.

* This term is due to M. Depéret; see De Lapparent, *Traité de Géologie*, 3me. éd., p. 1294.

Astian to Sicilian.

Red Crag.

Lam. *Pecten opercularis. Cardium Parkinsoni. Tellina obliqua. Mactra ovalis.*

Gast. *Buccinum undatum. Nassa reticosa. Purpura tetragona. Purpura lapillus. Natica mnltipunctata* (and several other species). *Trophon* (*Chrysodomus*) *antiquus. Trophon* (*Chrysodomus*) *contrarius* (a common "left-handed" form).

Norwich Crag.

Gast. *Turritella terebra* (= *communis*). *Trophon scalariformis.*

Chillesford Beds.

Lam. *Mya truncata. Cyprina islandica.*
Gast. *Littorina littorea.*

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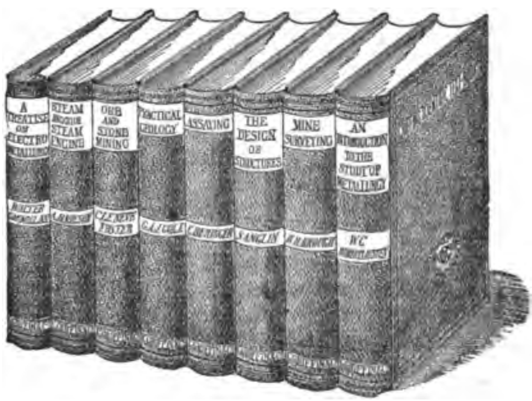

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